NASA SP-102

Philosophy Of Simulation In A Man-Machine Space Mission System

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FOREWORD

This report, prepared under Contract NASr-115, examines the philosophy of simulation as it pertains to manned space activities, with a particular orientation to research in the life sciences.

The manuscript was reviewed and evaluated by leaders in the scientific community as well as the NASA staff. Although there was varied opinion about the author's interpretation of the data compiled, there was nonetheless complete satisfaction with the level and scope of the study. It is anticipated that this study will become a basic building block upon which research and development within the space community may proceed.

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PREFACE

In the past few years, the art and science of simulation has become more and more important in the work of the aerospace engineer, life scientist, and systems instructor. This study is an examination of the philosophy of simulation as it pertains to manned space activities, with particular orientation to research in the life sciences.

An attempt is made herein to determine, by analysis of current and recent efforts, in what manner simulation can best contribute to the solution of manned space problems. From one who is neither psychologist nor engineer, the attempt may well seem presumptuous—and no doubt it is. At the same time, sublime ignorance reduces the likelihood of bias, and perhaps results in a more objective approach than might have been possible had one been pre-conditioned with psychological or engineering concepts.

Ignorance, however, is no excuse for error; and when error is found, as inevitably it will be, the responsibility must be mine. I acknowledge with gratitude, however, the criticism and comments of A. H. Schwichtenberg and E. M. Roth of the Department of Aerospace Medicine and Bioastronautics, and J. Szafran of the Department of Psychophysiology at the Lovelace Foundation for Medical Research and Education.

T. M. F.

INTRODUCTION

Beware lest you lose the substance
by grasping at the shadow.

AESOP, 550 B.C.
THE DOG AND THE SHADOW

The art of simulation is neither new nor is it confined to the design and use of complex electromechanical devices intended for training and research purposes. In fact, in its broadest sense, the art of simulation has existed since man drew his first picture in the sand or made his first model out of clay, and it has developed through the skills of the artist, the actor, the set designer, the illusionist, and more recently the information theorist, the psychologist, the mathematician, and the engineer.

One particular facet of simulation, however, is of concern in this paper: The simulation of elements of the environment and tasks found in a man-machine space mission system. It is therefore necessary to provide a definition for something that is more than an art but not yet a science.

Redgrave [53] defines simulation as a representation, or technique, which transforms, either iconically or by abstraction, selected aspects of the real world out of their resident framework into a form more convenient for the analyst's purpose. This is a broad definition, applying to every form of simulation.

A closer analysis is that of Ruby et al.[57] who define simulation as the representation of the characteristics of a system for the purpose of evaluating the performance of that system under various conditions. An even narrower interpretation is that of Westbrook,[72] who defines simulators as facilities which allow an analog representation of a particular control element, combination of control elements, or a complete flight-control-airframe-pilot system.

The first definition stresses convenience, the second performance, and the third control. Consequently, a new and nonpragmatic definition is suggested: Simulation is the art and science of representing the essential elements of a system out of their normal setting in such a manner that the representation is a valid analog of the system under study. This definition stresses the factor of representation but does not limit the purpose and use.

With the burgeoning cost in design and operation of today's aircraft and space vehicles, and with the increasing difficulty and, in some cases, impossibility of flight test development, simulators have become increasingly important in design studies and in the integration of man and machine. Even this, however, is not too recent a development.

Ringham and Cutler[54] outline an interesting history of flight simulators, noting that some of the earliest devices dated back to 1910 and consisted of actual moving aircraft supported by balloons, overhead gantries, and railway bogies. Other devices included a facility produced in France in 1917, whereby the variations in response and feel of an aircraft which occur with increasing speed were produced by applying compressed air to a pivoted fuselage.

In 1929, Roeder, in Germany, obtained a patent for a navigation trainer for vehicles in free space, including aircraft, airships, and submarines. This device, although not apparently put into production, used the principles of today's computer techniques in its operation.

The first instrument flying trainer was produced by Johnson in 1931 under British patent, and included a dynamic airspeed indicator and turn and bank indicators. The heading was determined by an integrator device associated with the rudder. The throttle operated a tachometer and influenced the rate of climb.

Dashpots were suggested to produce damping of control response but were not in fact used. The instructor set in problems on a second set of controls.

The work of Edwin Link in the 1930's and later was mainly responsible for the integrated simulator as it is known today; it is of interest to note a comment by Westbrook [72] that Mueller [41] in 1936 reported an electrical device for solving longitudinal stability equations and suggested coupling his device to hand controls for use in pilot training—hence anticipating the analog computer simulator.

The impetus of World War II produced great advance in the art and science of flight simulation. The development of analog and digital computers, the science of cybernetics, and servo-control and feedback techniques made it feasible to consider a realistic application of motion, control and display responses, and environmental representation to what, in effect, had been procedures trainers.

In the meantime, of course, particularly in the field of environmental test engineering, other devices were being developed to test the response of materials to such phenomena as sustained and impact acceleration, blast and shock, temperature, humidity, weathering, and the like. Many of these devices found application in physiological testing; the physiologists themselves were working in the fields of increased and decreased pressure and atmosphere composition, and were investigating man's limitations, while the human factors engineers and psychologists were investigating the man-machine interface. In other fields, information theorists and psychologists were examining the nature of information and the logic of training.

Thus, different approaches were being taken to the art and science of manned simulators, all of which began to come together in the evolution of the complex electro-optico-mechanical device found in the integrated space mission simulator of today.

CHAPTER I

NATURE OF SIMULATION

Simulation, as noted in the introduction, is more than the use of integrated mission simulators. Although this paper is concerned with the uses of simulation in man-machine space systems, it is wise to examine, if only briefly, the general theory and nature of simulation.

Redgrave [53] points out that simulation in its broadest sense may be considered as any type of representation of reality with varying degrees of realism, or different degrees of effort, to include the details of the environment within which the subject of the simulation resides. The efforts to include richness, however, do not necessarily imply that the details of the environment or the object being simulated be incorporated exactly as they appear to the real world. The details may be simulated as functions rather than physical entities. Thus, as will be noted in the discussion of visual requirements, a visual environment may be represented adequately under certain circumstances by a suitable display of crosshatched lines (Barnes[5]). On the other hand, a radar display may accurately reproduce the form of its real-life counterpart, and a rendezvous and docking simulator may require the use of a three-dimensional scaled replica.

TYPES OF SIMULATION

Simulation may be concerned with models, with gaming, or with both. A model is a transformation of real-world parameters and may be abstract, as in a mathematical representation of the human response to impact shock, or concrete, as in the mock-up of a cabin design. It may be static, as in a display panel design, or dynamic, as in the extreme case of a six-degree-of-freedom integrated mission simulator.

Gaming, on the other hand, may involve anything from a study of simulated war maneuvers to simulation of the situation involved in landing a lunar exploration vehicle.

Belsley [6] notes that the ideal approach to simulation requires control of the process to be studied in order to define the problem areas systematically, to identify significant variables, and to assess the effect of variables on the overall system and its degree of acceptability.

For simple static studies, this is not a difficult problem. It is relatively easy, for example, to build a mock-up of a display panel and to identify the optimum positioning of specific displays. For man-machine system studies involving complex machines and diverse tasks, this experimental approach is difficult to attain without putting man into the loop as a functioning entity.

In the implementation of this process, a generalized functional model of man-machine system operations should be considered in determining which of the functions are represented in the specific system to be simulated. Such a model (fig. 1) is presented by Roscoe (personal communication). In this model, the various classes of functions performed by men and/or machines in an operational environment are represented, and their possible interrelationships are diagrammed.

Whenever man employs any agent as a tool to mediate the accomplishment of a function, a man-machine system exists. The tool may be as simple as a stick used as a lever, a rock used as a projectile, or a sling used to project the rock. The tool may be a complex digital computer, a synthetic array radar, or a rocket motor. Strictly speaking, it does not matter whether the tool is animate or inanimate; the essential element is the use of anything as a mediating agent.

In a highly complex spacecraft system, all manual, semiautomatic, and automatic functions shown in figure 1 might be rep-

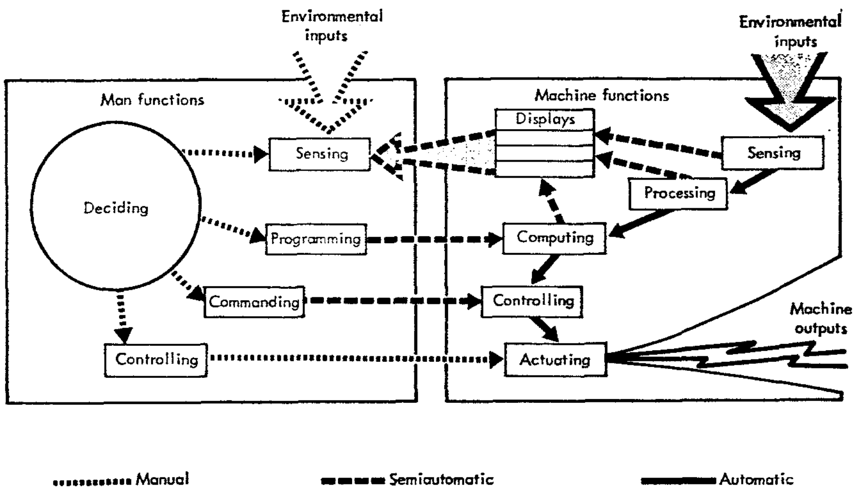


Figure 1.—Functional model of man-machine system operations.

resented. At the other extreme, for example in a primitive weapon system such as a man throwing a rock, all functions are human save one: the human functions are sensing, deciding, and controlling; the automatic function is the actuating done by the machine (the rock) when it impacts its target at the termination of its trajectory. The system output is damage or injury to the target.

If one employs a sling to project the rock, the sling, as well as the rock, becomes a mediating or actuating agent; consequently, the combination is more readily thought of as a man-machine system. Similarly, a man-machine system may be completely automatic, save for the decision to command it into operation.

In such systems, all other decision functions have been performed by the designer or the programer before the command decision is made to set the system into operation.

Thus, the general model is obviously designed to encompass the functions and functional relationships of any system, although a given system may not perform all the functions represented. While a system may be almost completely automatic or manual, no system is truly either. Systems of practical interest in the present context are typically semiautomatic, involving both automatic and manual sensing and various connecting processes mediated through displays and controls, all leading to the determination of machine outputs.

By synthesis of the relevant aspects of this generalized model, according to the requirements of the system to be simulated and by integration of actual hardware and digital/analog elements, a

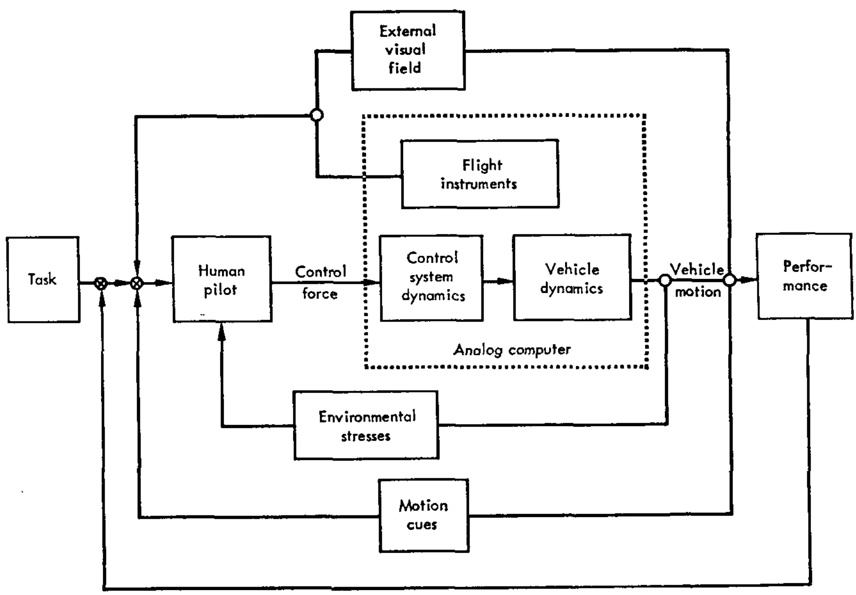


Figure 2.—Block diagram of piloted flight simulator. (Source: Belsley [6])

simulation system can be designed to meet appropriate requirements. A block diagram of a complex dynamic simulator is illustrated in figure 2. As Belsley [6] points out, the task in this situation is presented to the subject-experimenter in such a form that he can identify and assess its specifics and give a subjective rating of his situation. At the same time, an objective assessment of the performance of the man-machine system can be undertaken.

Frequently, however, it is necessary to include the response characteristics of the controlled element, in this case the vehicle, and to vary them, as well as the extra-vehicular environment, at will. These response qualities and quantities must be read back to the operator in such a manner as to indicate readily the status of the vehicle and to provide cues, proprioceptive and other, adequate for conducting a required task. Thus, a manned space simulator may require, with varying degrees of sophistication, operative displays and controls, a realistic physical environment, and a semblance of vehicle motion. The physical environment can be recreated in terms of pressure, temperature, external vision, etc. Simulation of displays, controls, and, in some cases, motion requires a different approach.

Simulation can be accomplished by considering the dynamic response characteristics of the vehicle and displays as functions of time, deriving the necessary equations, programing a computer for their continuous solution, and converting the resulting solutions into signals for use in driving servos. Thus, certain response characteristics are expressed as equations which can be translated into terms of gains, natural frequencies, and damping ratios, which become the dynamic descriptors of the vehicle. Similarly, other signals can be used to drive displays and control presentation of the environment.

In this connection, McNulty [35] stresses that an operation can be simulated only to the extent that it can be defined in a manner suitable for programing, and that the simulation equipment has its own characteristics which are imposed upon those of the operations simulated. Within these constraints, however, the motion can be described in terms of a mathematical model.

Essentially, six dynamic equations must be solved, representing translation along three axes and rotation about three axes. Their solution involves summation, integration with respect to time, multiplication, and trigonometric resolution. Calculation of the aerodynamic translations, forces, and moments involves generation of arbitrary functions (e. g., functions of Mach number, altitude, etc.) and division. Solution of the propulsion equations, which gives such outputs as thrust and rpm, may involve functions of generation, integration, summation, and multiplication.

The computers used to provide these requirements may be analog, digital, or frequently combinations of both. Analog computers, with their capacity for virtually instantaneous integration and for function generation, lend themselves to use in controls and displays. At the same time, however, many techniques used incorporate electromechanical servocomponents into the system which, because of their mass, friction, and backlash, impose undesirable characteristics on the simulation. In addition, analog computers are designed to be operated over a relatively small voltage range, scaled so that the maximum value of the variable is represented by the maximum voltage of the computer. In such cases, the minimum value significant to the operator may be below the system noise level, and since the system must be designed to operate above the noise level, the resulting time delays will give rise to nonlinearities in performance.

Consequently, despite their slower operation, the use of digital computers is becoming more and more common, with digital-analog converters used where required. A typical example is found in the UDOFT digital simulator (Wargo et al.[70]). This simulator has a major advantage of flexibility, in that representations of the dynamics of different vehicles can be made in the output. At the same time, digital computation has high inherent accuracy and reproducibility.

PURPOSE OF MANNED SIMULATION

Reduced to essentials, the purpose of simulation is to provide a tool for the acquisition of knowledge under circumstances where the acquisition of that knowledge from the original source would be impracticable. The reason for the impracticability may lie in economics or safety, or in the fact that variables cannot be adequately controlled. It is not economical to build a progressive series of spacecraft, systems, or subsystems as design and development proceed, nor is it economical or safe to use production craft for crew training. Thus, it has become necessary to build a variety of simulators to provide basic data under controlled conditions.

Westbrook [72] points out that simulators are used where basic knowledge is weak; where complex interrelationships are not fully understood; and where calculations, estimates, or judgments are not trusted. He predicts an increasing trend toward more and more complex simulation which can devour talent that might be better used in design and development. In addition, he draws attention to two other dangers of simulation: simulation without relation to the problem at hand, and the development of more sophisticated simulation.

Bearing in mind this warning, simulation nevertheless has had a large place in manned space mission systems, specifically in relation to engineering design; evaluation and validation of concepts, materials, and man; development of procedures; and training. It is perhaps not surprising that in the literature the most important uses of simulation cited by an author appear to vary with his background discipline.

To the design engineer, a simulator is largely a device to provide him with data for his design studies. To the human factors engineer, simulation is a means of determining optimum displays and cabin layout. To the environmental test engineer, it is a method of testing the integrity of systems, subsystems, and components under hazardous environments. To the aerodynamicist, it is a way of examining the dynamic stability of a system under flight conditions. To the environmental physiologist, simulation is a tool for testing man's response to stress. To the psychologist, it is a system for measuring man's performance. To the instructor, it is a sophisticated training aid, and so on.

Numerous authors, Adams,[1, 2] Barnes,[5] Clausen,[19] Gagne,[23] Little,[32] Obermayer and Muckler,[44] Pecoraro,[45] Redgrave,[53] Schueller,[61] Simon,[63] Smith and DeRocher,[64] Urmer and Jones,[69] and Westbrook,[72] have listed uses and potential uses of simulators in manned space flight systems, and by adapting their views and adding others, the following list has been devised.

I. Design engineering
   A. Development of criteria for:
      1. Vehicle engineering
         a. Structural
         b. Aerodynamic
         c. Systems
         d. Subsystems and components
      2. Sensor, signal processor, and display engineering
         a. Radar
         b. Infrared
         c. Electro-optical, including laser and TV
         d. Acoustical

3. Human engineering
    a. Habitability
    b. Instrument and indicator display and operation
    c. Control design, location, and operation
    d. Man-machine integration
4. Personal protective equipment

B. Demonstration of conceptual feasibility of a design

II. Evaluation of systems, components, and materials

A. Validation of design studies
B. Determination of structural integrity with and without stress
C. Determination of performance of systems, components, and materials with and without stress
D. Evaluation of personal equipment
E. Prediction of response of systems, components, and materials to prolonged stress

III. Evaluation of man's capacities

A. Determination of human capacities, physiological and psychological limitations, in normal operating conditions and under stress
B. Determination of performance and proficiency of man and man-machine systems in normal operating conditions and under stress
C. Prediction of man's performance under, and physiological response of man to, prolonged stress

IV. Procedures and requirements

A. Allocation of function to man and machine
B. Determination of personnel requirements

C. Determination of operating procedures
   1. Routine
   2. Emergency
D. Determination of maintenance procedures
E. Determination of logistic support requirements
F. Development and evaluation of tactics
G. Determination of work, rest, and activity schedules

V. Selection and training
   A. Selection and classification of potential and partially trained astronauts
   B. Development of training programs, devices, and standards
   C. Determination of areas of special training
   D. Initial mission training for new astronauts
   E. Proficiency training for experienced astronauts
   F. Special training for special areas
   G. Transition training with transfer to new vehicle
   H. Prediction and measurement of proficiency
   I. Experience in stressful environments
   J. Training for ground handling crew

It is clear that a distinction must be made between simulation for training and simulation for research, and, in the research field, a further distinction between operational or engineering simulation and psychophysiological simulation must be made. The purpose of operational simulation is to study how the machine system is modified by putting man into the loop, the aim being to optimize the combination. The object of psychophysiological simulation is to study the effects of the man-machine environment on man.

This paper is not primarily concerned with operational simulation, except insofar as it forms an interface with man as exemplified by human engineering studies. It is more concerned with the psychophysiological type of simulation as exemplified by its use in the evaluation of man's capacities, the development of space mission procedures and requirements, and the selection and training of astronauts, as detailed in the above listing.

CHAPTER 2

PREREQUISITES FOR SIMULATION

TASK TAXONOMY

Unfortunately, it is all too easy to delve into a simulation program without full consideration of the multitudinous factors involved and to use the results obtained as indicative of those found in the actual situation. It is necessary first to make a thorough analysis of the situation to be simulated and the purpose of the simulation, particularly when man, with his subjective limitations, is included in the simulation. In this regard, Urmer and Jones,[69] have used the term "task taxonomy" to describe the analysis and point out that to obtain reliable and valid quantitative data on man's performance in spacecraft, a taxonomy must be developed which will permit the data acquired from part-task simulation to be incorporated into estimates of the same performance in the total system. Urmer and Jones note that, while these performance estimates will be gross initially, they will become refined as larger quantities of data are accumulated and will eventually become an invaluable tool for human engineering in spacecraft.

Thus, an analysis of the nature of the task must first be made —whether it is predominantly concerned with training, evaluation, and development of systems and hardware or with an assessment of man's response and capacities. Thereafter, the elements or parameters of the task must be examined with the object of selecting for integrated or part-task simulation those elements considered critical to the system being simulated.

For a manned space mission system, the task might involve any aspect from a test of personal equipment to a human factors study, or a whole or part mission. It would be desirable to simulate all situations as completely as possible, but the cost in time, computers, and personnel make this prohibitive, and, of course, not all aspects of the environment can be simulated. Hence, it becomes necessary to be selective.

Urmer and Jones [69] discuss this task analysis problem in a paper in which they examine criteria for spacecraft simulation. They consider that a time-based record of the total required performance of the crew must be prepared. It might be noted, however, that this alone might be one of the tasks for which the simulation is undertaken. They emphasize the importance of considering all aspects of the environment, display-control factors, and sensory factors, noting that even minor changes can have an unpredictable effect on performance. This influence can be either positive or negative.

Moderately adverse environments, which might be considered detrimental during analytic procedures, may result in increased motivation which actually improves performance. This fact was particularly observed by Chambers,[18] during his work on simulated launch and reentry procedures with astronauts.

The problem of completing a task analysis for a simulated mission is a difficult one, particularly where little is known about the factors involved. One approach lies in the development of a matrix system in which different aspects of the expected environment are examined in terms of their potential interaction physiologically and psychologically with man. Complex matrix evaluations of simulator problems have been suggested by Hoover (personal communication), and a limited matrix is defined by Simon,[63] who examines interactions between the environment and aspects of human performance.

Another and perhaps more direct approach is that taken by

Hopkins,[29] whose paper is concerned with the development of operational sequence diagrams for manned space flight but has direct application to the determination of human operator function in manned simulators. Using a systems type of analysis, he initially describes a given mission in general terms, from which a number of specific mission requirements can be derived and phases of the mission isolated. Each specific requirement may then be represented by a "key" event which has to be completed to satisfy the requirement.

Table 1 illustrates the type of analysis that might be undertaken for a shuttle mission between earth and an orbiting satellite.

After isolating the phases and "key" events, the next step consists of diagramming alternate sequences of events which involve different combinations of man-machine function. These events are presented with geometric symbols to show courses of action performed automatically, courses of action initiated and/or implemented by the human, and information required by the human. Event sequences are then analyzed to determine those with the highest probability of successful mission accomplishment. The final result is a diagram indicating the following: (1) alternate sequences of events which will culminate in successful completion of major mission requirements in spite of occurrence of unfavorable but predictable and counteractable events, (2) sequences of events that would culminate in the termination of a mission prior to its successful completion if certain unfavorable events that cannot be successfully counteracted occur, and (3) the system functions, both normal and emergency, in which the operator is involved.

An illustrative diagram is included in Hopkins' original text, and should be consulted if required; unfortunately, it is too large and complex for reproduction.

The occurrence of additional and unexpected interactions must be borne in mind. For instance Urmer and Jones[69] cite

Table 1.—MISSION ANALYSIS OUTLINE
(SOURCE: HOPKINS [29])

Major mission requirement	Mission phase terminated by accomplishment of mission requirement	Key event signifying accomplishment of mission requirement	Necessary conditions of occurrence of event signifying accomplishment of mission requirement
Initiation of powered flight	Prelaunch	Delivery of firing signal to first-stage rocket motor	Time-to-go to predetermined launch time equals zero; pilot and ground crew agreement system ready for launch
Attainment of planned orbit	Boost	Burnout of injection stage rocket	Velocity, altitude, and velocity vector within specified limits
Rendezvous with destination satellite	Rendezvous	Safe mechanical attachment to destination satellite	Correspondence, within very close tolerances, of orbital elements of the two satellites
Departure from orbit	De-orbit	Burnout of retrorocket	Burnout at correct time; speed, altitude, and velocity vector within specified limits
Attainment of aerodynamic flight	Reentry	Attainment of specified "safe" velocity	Reentry into atmosphere at small "safe" angle; glide program to reduce orbital speed and avoid overheating
Arrival in vicinity of landing base	Terminal navigation	Arrival at entry notch within acceptable velocity and altitude limits	Attitude control program as a function of velocity and geographical position during atmospheric glide
Controled landing at designated base	Landing	Termination of landing roll or slide in safe condition	Attitude control program as a function of velocity and geographical position during landing approach

a situation in which the wearing of pressure suits during a simulation study did not affect routine control performance, but did produce a decrement as compared with shirt-sleeve performance when external disturbances were included in the simulation.

After the task has been analyzed, it is then necessary, if other than a training task, to examine the methodology of the simulation. Ruby et al.[57] relate this to the classical scientific method and show that it has elements of definition, hypothesis, experimental plan, equipment, data collection, data analysis, and conclusion.

Definition of the problem lies, of course, in the task analysis and allows formulation of a *hypothesis,* although in some simulation exercises, such as the assessment of the human response to environmental stress, the hypothesis is only implied.

According to Ruby et al.,[57] the *experimental plan* includes consideration of measures and statistical analysis, as well as the actual design of the experiment. It is perhaps better, however, to consider statistical analyses here under the heading of data processing, bearing in mind the requirement to consider the need for data selection and data processing in the planning stage.

The question of the relevancy of *performance measures* has received much attention, particularly in the realm of simulation. With many variables frequently involved and requirements for subjective assessment, the measurements made may have a tenuous relationship to the parameters measured. In this regard, a comment by Smode et al.[65] is apposite:

> Present measures and measurement methods frequently provide less than complete information. What behaviors are critical to proficient performance, what complex of behaviors is involved in criterion performance, what are the best measures of particular activities, under what range of conditions should measurements be taken, etc., are recurring questions for which the answers are not obvious and/or are only, at best, approximations. Decisions regarding what components of behavior to

sample and the conditions under which observations should be made are, in many instances, of necessity a matter of expert judgment of experienced individuals. Classes of measurements obtained are often indeterminately associated with overall proficiency. In some instances, measurement may be so difficult that the operating practice is to obtain what is measurable rather than what is desired.

Although this was stated with respect to performance in flight, it is equally applicable to the science of human measurement in general. Nevertheless, it is feasible to approach measurement in a logical fashion. Measurement is the assignment of numerals to objects or events according to rules. The logical approach is illustrated in two papers on performance measurement in flight simulation by Obermayer and Muckler,[43, 44] who performed studies to establish an ordering of measure classes and to suggest criteria by which performance measures could be selected. Although the applications are with respect to guidance and control, they have some bearing on the general problem. Obermayer and Muckler analyzed six previously completed simulation studies, two of which were feasibility demonstrations involving manned control of large launch vehicles and manned lunar landings. One concerned an altimeter comparison; two referred to the development of a pilot-analog and a Monte Carlo model for control situations; and the final study was concerned with the simulation and measurement of the handling qualities of an aircraft. They showed that in these studies a wide variety of measurement methods were used, including continuous and discrete measures, directed and abstracted measures, and objective and subjective measures, according to the investigators' preferred method. No systematized organization appeared to be present.

Noting that all the duties were oriented toward aspects of guidance control, Obermayer and Muckler established a system of criterion categories for the evaluation of guidance and control systems, based on the work of Schmitt,[60] and using as their criteria the qualities of stability, response, adaptability, reliability, and acceptability. They then reexamined the studies mentioned to determine what, if any, measures had been made that would provide an evaluation in terms of their established criterion categories. The results of the evaluation are indicated in table 2.

Table 2—EVALUATION OF MEASUREMENT METHODS [a]

Studies cited	General criteria				
	Stability	Response	Adaptability	Reliability	Acceptability
Manned control of launch vehicles	X	O	X	?	
Lunar landing		X		?	
Altimeter study	?	X	X	X	X
Pilot control analog		X			X
Monte Carlo model	O	X	O	?	
Handling qualities	?		?		X

a. X = Measurement taken
O = Measurement not possible
? = Inferences from measures possible

Thus, in terms of the criterion categories, only some of the measures provided useful information. Unfortunately, Obermayer and Muckler do not state the extent of redundancy of the other measures, but go on to show what measures could be made to satisfy the criteria. In regard to the general problem of measurement, Obermayer and Muckler[44] state: "If measurement is viewed as an information collection process, it can be argued that, if the information requirements are specified, the desired measurement set should be directly implied. In short, if one knows what it is he wants to measure, then it should be clear *what* to measure."

In a personal communication, E. R. Jones emphasizes the importance and difficulties of crew performance measurement in space systems, simulated and real. He points out the following factors that require consideration in defining measurement requirements:

(1) Man-machine interaction: Measurements must consider the interactive effects of the man and the equipment. This measurement of man's performance must be interpreted in the light of equipment bias, unreliability, and precision for all of which measures must also be obtained.

(2) Validity of measurements: Comparability of measurements obtained in a simulator with those obtained in orbit must be considered. As pointed out elsewhere, this can only be done by actual validating experiments correlating the simulation with reality.

(3) Reliability of measurements: Random variations can occur in the simulation equipment, the measuring equipment, and the crew. A major advantage of a simulator over a flight vehicle is that the characteristics of the simulation and measurement equipment can be better controlled and can permit the measurement results to reflect more accurately the response of crew performance.

(4) Objectivity of measures: Wherever possible, performance measures should be objective. If necessary for "gap-filling," these may be backed up by subjective evaluations, which in turn should be standardized as much as possible.

(5) Diagnostic and direct measures: Direct measures, according to Jones, are those that clearly assess the output of this system and have a clearcut operational meaning, for example, with respect to success in correction of a flight malfunction. Measures of this type may not be attainable in a simulator because of lack of precise fidelity. Diagnostic measures, on the other hand, provide information on the efficacy of proper sequencing of events that must be accomplished for correct completion of a task. Measures of this type indicate how and where man can

most successfully participate in a system and why a required operational result is not achieved; both direct and diagnostic measures are required. Early in development of the simulation system, diagnostic measures will predominate. As simulation equipment fidelity increases as a result of operational verification and design refinement, more direct measures will become available.

(6) Individual and crew measures: Measures are required to determine the relative contribution of each crewman to system operation. These measures will assess the extent of crew cooperation and provide information for designing operational systems and for interpreting the results of performance in the actual vehicle.

(7) Infrequent events: Many elements of system and human performance that are of measurement interest occur only occasionally. A potential advantage of a simulator is its ability to obtain more observations on critical phenomena or to stress the crew more than is practical in the operational situation. Measurement systems must allow for expansion to meet these more frequent requirements.

(8) Problem reproducibility: A simulator has the potential advantage of allowing repeated measurement of the response to a set problem known to the instructor but not to the crew.

(9) Classes of measurement: Various types of measurement may be required, with or without combination, in determining the response of the man in the man-machine system. These measurements include:

(a) Time: Time measures may be concerned with the rapidity with which a task can be accomplished, or the accuracy of the accomplishment within a given time limit.

(b) Sequence: Sequence measurements are concerned with the accuracy of accomplishment of a series of tasks, each of which is dependent upon the previous. The measures may involve time limits, either for the total task or individually for the components.

(c) Precision: These are measures of the terminal precision of a sequence of activities, and require even greater precision in the measuring device.

(d) Continuity: Measures of continuity are directed primarily towards tasks in which tracking is involved and include measures of error amplitude and error frequency. The latter may in turn involve measures of the error power density spectrum, which indicate the rapidity with which error corrections are made and provide a measure of the amount of difficulty encountered in maintaining a given track.

(e) Complex discrimination: These measures are concerned with the crewman's response to a complex pattern of cues from which he must diagnose the state of a system and arrive at a course of action. In many cases, the correct response will not be absolute but must be assessed on a probability basis. Measures of this type require simultaneous recording of system environmental and human variables.

Returning again to the analogy between the classical experimental method and a simulation exercise, Ruby et al.[57] note that *subject (or crew) selection* is part of the experimental plan and emphasize that subjects must be selected from a population which bears a relation to the population to be utilized in the real-life situation. In fact, to some extent, when a subject is selected to take part in a manned space simulation, he is, in effect, simulating an astronaut. Just as it is wise to utilize, wherever possible, actual hardware in simulation, similarly it is wise to utilize the astronaut population or a closely related population if possible. This same belief is echoed by Grodsky and Bryant.[26] As will be noted later, while selection of astronaut types is useful when one wishes an astronaut-type response, there are situations in which it is perhaps more useful to select as subjects individuals who do not have the "superman" capacities of the astronaut.

Following this analysis, the question of *equipment selection* becomes logical. On the basis of task definition, hypothesis, and experimental plan, the type and extent of equipment required becomes clear. However, in practice, implementation of the requirement is not always so logical. Ideally, the required equipment would be built, bought, or rented, but in practice, because of economic factors, it is frequently necessary to modify existing equipment to meet the need. This leads to inevitable compromise, frequently in the fidelity of the system. The question of fidelity is considered subsequently.

Problems of *data collection and analysis* have largely been considered in the discussion of measurement. Data may be acquired by subjective, analog, or digital techniques, each of which has its advantages and disadvantages; but while the inherent dangers in subjective methods are obvious, the dangers of analog and digital methods are less so. In the latter case, the potential error in the method is generally known and measurable; danger lies in the selection of the measure and interpretation of the data. Each, however, is open to conscious or unconscious bias on the part of the investigator.

The *conclusions*, of course, are the ultimate aim, and their nature will depend on the purpose of the simulation. It is essential, however, that conclusions be interpreted in the light of the simulator characteristics. Conclusions drawn from work on a simulator with one set of characteristics are not necessarily applicable to another with different characteristics—and perhaps even less suitable for extrapolation to reality.

ENVIRONMENTAL TAXONOMY

In manned simulation, particularly of the more complex type, one of the greatest problems lies in an adequate representation of the environment—both of the internal cabin and the external milieu. Ideally, the objective would seem to be to represent, under controlled and non-hazardous circumstances, all the factors in the actual environment. To some extent, with the notable exceptions of radiation and weightlessness this can be achieved. However, as will be shown, it is unnecessary to reproduce the literal environment in all situations, and in many circumstances an illusion of the environment will suffice.

What then are the factors in the environment that significantly affect the manned space system and how faithful need be their reproduction?

Man's physical environment, and by that is meant those physical phenomena under the control of natural laws that influence his physiological and psychological responses, may be classified as follows:

I. Radiation
   A. Cosmic and nuclear
   B. Solar—infrared to ultraviolet
   C. Microwave and electromagnetic

II. Force fields
   A. Weightlessness
   B. Impact acceleration and blast
   C. Sustained acceleration
   D. Vibration, buffeting, and tumbling
   E. Noise

III. Atmospheric
   A. Reduced pressure
   B. Increased pressure

C. Composition
D. Temperature and fire
E. Humidity
F. Chemical toxicity
G. Biological toxicity
H. Meteorites, meteors, and dust

REQUIREMENTS FOR ENVIRONMENTAL SIMULATION

It would seem a reasonable assumption that not all aspects of the environment need be simulated in a manned mission simulator. Simulation need be attempted only for those elements of a situation that are critical to the task at hand. The obvious question of what is critical to the task at hand arises. The answer is far from being known at this time, but is considered, at least in part, in chapter 3.

Meantime, assuming that maximum verisimilitude is desirable for an integrated mission simulation, the elements of the environment which should be represented in such a simulation are discussed in the following paragraphs.

Electromagnetic radiation

While all portions of the electromagnetic radiation spectrum are of significance to the astronaut and his vehicle from the point of view of operation or hazard, the most significant portion is undoubtedly the visible spectrum. This will be examined in another section.

The radio wave region may result in a noise input to the communication system and for this reason, in a fully integrated mission simulation, it deserves consideration as an intermittent nuisance, as well as for communication.

It seems unnecessary, and perhaps even dangerous, to consider simulation of the infrared and ultraviolet spectra in a simulator that is intended for training and familiarization. Although the former contributes to the heat load of the vehicle, management of heat load falls within the content of the cabin environmental control system, the malfunction of which can be readily simulated. Similarly, nothing is to be gained in these circumstances by simulation of the ultraviolet spectrum.

Ionizing radiation

There is no doubt that ionizing radiation in sufficient dosage is one of the astronaut's most serious hazards. However, since its effects at subclinical levels are beyond human perception, it is unnecessary, as well as dangerous, to reproduce it in a simulator except where its effects are under specific investigation; and except for training purposes, its existence and intensity should be displayed artificially on dosimeters designed to record integrated dose and dose rate of high-energy particles. There is probably no requirement in training to record soft X-rays and low-energy particles. For research purposes, of course, controlled radiation can be introduced into a specially designed simulator.

Condensed matter

Condensed matter is made up of meteorites, meteors, and dust. Its effects, depending on the size and velocity of the particles and the structure of the vehicle, may result in penetration with decompression, material, and human damage; erosion with malfunction of optical systems; and perhaps change in heat regulation or structural damage to the vehicle. Consideration of erosion and noise is perhaps somewhat academic, since in the case of the former it is unlikely that optical properties of external parts or reviewing systems will be altered significantly within less than a year (Whipple, quoted in Hart [28]); and in the case of the latter, the only value in reproducing the noise would lie in verisimilitude. In lunar landing simulators, it may be necessary to reproduce visually the effects of dust. Because of attendant decompression, however, penetration requires simulation, although an actual pressure drop is not readily practicable unless the simulator is located inside an environmental chamber. The effects of decompression can be simulated on displays, and the experience of actual decompression can be provided in altitude chambers.

Force fields

Acceleration in its various forms, including vibration, buffeting, and tumbling, produces highly significant effects on the vehicle, its systems and subsystems, and the crew. Much work has been done with centrifuges, rocket sleds, and vibrational and impact devices to determine their effect on vehicle structure and function and on human tolerance, performance, and physiology. The devices used for this purpose belong in the category of partial-environment simulators, in which only one major element of the environment is varied under circumstances that frequently bear little relationship to those expected in a mission situation. Consequently, the results can be extrapolated to those expected in a mission simulation, or to actuality, only with caution. This question of part-task as opposed to whole-task simulation is reexamined in a subsequent section.

However, despite the fact that the available information has largely been obtained under artificial circumstances in part-task simulators, there is little doubt that the effects of acceleration in its various manifestations are sufficiently significant. Were it not for major difficulties in engineering and cost, acceleration potential would be incorporated into an integrated mission simulator with little question. Because of these difficulties, it is necessary to make a decision as to whether the cost and complexity of the required facilities are justified by the advantages accrued. Unfortunately, information on which to base such a decision is far from complete. In a later section, the whole question of provision of motion, or a semblance of motion, will be discussed.

Meantime, it may be stated that, assuming maximum verisimilitude is considered desirable in a mission simulator, the provision of acceleration potential in its various manifestations should be considered in light of the cost; otherwise, acceleration should be included only where its effects are considered critical to the study or training at hand, and then perhaps it should be applied only in a partial-environment simulator.

Reduced gravitation and weightlessness are also highly significant factors in the environment of a space vehicle and are very much in need of simulation. However, despite several ingenious approaches, no satisfactory simulation is yet possible.

The noise environment, particularly that which accompanies the preorbital and reentry maneuvers, is an aspect of the environment that requires simulation for verisimilitude. Roscoe (personal communication) recommends consideration be given to the following aspects of noise environment:

(1) Ambient sounds, indigenous to system operation or external sources

(2) Verbal communications

(3) Coded communications via auditory displays

Atmospheric environment

Since the cabin atmosphere is the astronaut's immediate environment, it is desirable, particularly for those studies involving aspects of habitability, that actual conditions of gas composition, pressure, temperature, humidity, and toxic contamination be reproduced as closely as possible, using, as much as possible, the actual spacecraft hardware, architectural design, and layout. As noted at the beginning of this section, simulation should be attempted only when the situation is critical to the task at hand or for research purposes; when habitability is not a feature and maximum verisimilitude is not required, special atmospheric simulation is not required.

CHAPTER 3

FIDELITY, REALISM, AND TRANSFER OF TRAINING

The question of fidelity of simulation is one which has plagued designers and users of simulation more than any other. Fidelity, of course, refers to the extent of the resemblance between the real-life situation and the representation of that situation. Ideally, a completely realistic representation would seem to be the objective. This, of course, is impossible. Not only would it defeat the ends of economy, safety, and control of variables for which a simulator is used, but, in point of fact, if carried to the ultimate, it would no longer be simulation but an actual reproduction of the situation. Thus, the requirement of fidelity lies in providing a realism adequate for analysis of the experimental situation and satisfactory for a high positive transfer of training.

Jones (personal communication) considers there are two elements to fidelity, the first being the presence in the simulation of those elements essential to provide the required response, and the second being duplication of the situation to the extent that subjects accept the replica and are motivated to use it. The second criterion applies primarily to training simulators. It must be noted, however, that the fidelity demanded depends upon the purpose of the simulation. For engineering investigations, such as aerodynamic response and control problems, a faithful representation of the vehicle characteristics is required; for psychophysiological investigation of human response to stress, a real controlled stress must be reproduced; for training and familiarization, the semblance of the environment is required.

Orlansky (personal communication) draws a distinction between accuracy of simulation and realism. He defines accuracy of simulation as the extent of physical duplication of equipment and environment—a definition which is perhaps equivalent to that of physical fidelity. He considers realism as the accuracy of physical appearance to an observer—perhaps more commonly referred to as "face validity."

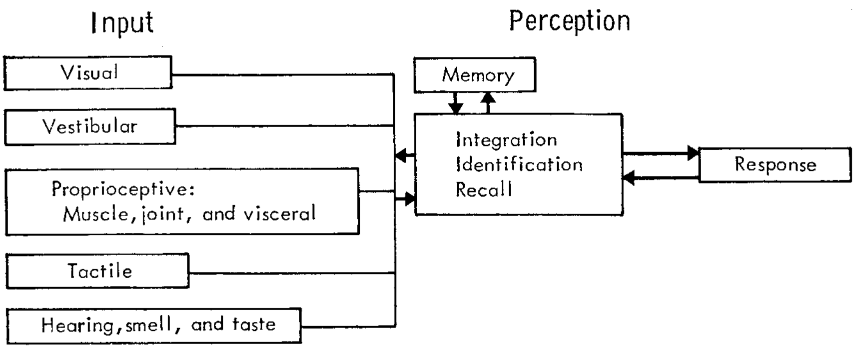
From the point of view of human response, Buddenhagen and Wolpin [13] recognize three classes of criteria for fidelity: physical fidelity, psychological fidelity, and perceptual fidelity. Physical fidelity is the degree to which simulation represents the physical properties of the operational equipment and environment. Psychological fidelity is the degree of psychological equivalence between the operational situation and that presented by the simulation. Physical fidelity is a fairly simple concept and relates the actual physical appearance and characteristics of the simulation and real world. It is possible, however, to have a physical model, which, because of its controls, response, and environmental relationships, bears little resemblance in operation to the real-world operation. For a system in which the response of man is a factor, such a model would provide little in the way of operational realism. In consequence, for the sake of realism, it is necessary to introduce into the model as much psychological fidelity as feasible. This in turn leads to design difficulties, some of which, at least, can be reduced by employing the concept of perceptual fidelity in which the effect of psychological fidelity is obtained without actually reproducing the full operational situation. Buddenhagen and Wolpin define the term "perceptual fidelity" as a measure of the subjective judgment of the accuracy with which the simulator presents the physical characteristics of the environment.

Perceptual fidelity is contrasted with physical fidelity in that it takes into account the psychological aspects of the response of the operator's senses to the actual and simulated physical environment. In the case of the visual sense, for example, a simulation may yield a low physical fidelity but a reasonably high perceptual fidelity by taking advantages of nonlinearities in the human visual response. Up to about 100 millilamberts, visual acuity increases with luminance. Beyond this value, it increases very little, and, consequently, the perceptual response of the human observer increases very little. Thus, for normal training situations where extremely high ambient luminances are of no particular concern, it may be concluded that visual fields with more than 100 millilamberts luminance are perceptually equivalent, and a simulation display technique that is capable of generating 100 millilamberts possesses almost 100-percent perceptual fidelity.

Lybrand et al.[34] use the term "phenomenal equivalence" to describe a similar relationship. They point out, however, that the only practical way of assessing the degree of phenomenal equivalence is by trial and error, whereby presentations devised on the basis of available evidence are presented on a simulator to experienced operators (e. g., astronauts) who decide, on the basis of careful judgment, whether the presentation has the qualities demanded. This method, although highly subjective and open to criticism, is the one in practical use.

PERCEPTION

The key to fidelity then, in a system intended for training purposes, lies in satisfying the requirements of perception. Perception is a complex process in which sensory inputs are integrated with the assistance of memory, cross-referencing, and feedback to produce a pattern which results in recognition and identification. This in turn leads to an effector response if one is required. This process is represented in the following sketch.



Franks, in an unpublished presentation, showed the relationship of perception to orientation, noting that orientation in its broadest sense is achieved when perception is true and complete. Attainment of maximum perceptual fidelity is a modification of this process and is achieved when perception is apparently true and complete; in actual fact, it is complete but false in that it provides only an illusion of truth. The art of perceptual fidelity in simulation resides in providing the illusion. Thus, the sensory receptors might be regarded as transducers which always transform the energy of their signal input in the same way. The object of simulation is to present a signal to the receptor representative of the false world, which is transduced in a manner identical with that from the real world so that the subject becomes oriented to the artificial world.

CRITICAL STIMULI

The criticality of parameters selected for simulation in an operational research situation depends, as has been noted, on the nature of the research. Commonly, since the relevant factors are not known, it is necessary to reproduce all, or most, of the properties that could conceivably affect the environment. Not all stimuli, however, are critical with respect to achieving the perceptual fidelity that satisfies some elements of training requirements; the measure of this lies in the degree of transfer of training occurring with and without simulation of particular stimuli. Examination of the requirements for transfer of training requires consideration of what George and Handlon [24] refer to as the theory of expectancies, which is discussed by Lybrand et al.[34] According to this theory, an individual has stored memories, or beliefs, from which he can determine the outcome of a particular response or set of responses to stimuli. These represent the accumulated effects of training and experience. At a given point, relatively few of these beliefs influence behavior. These beliefs are further conditioned by the action of stimuli from the environment and motivational factors from within the individual and become converted into expectancies. At a given decision point, the individual scans the range of expectancies present and selects a particular expectancy on which to base a response. A change in behavior results when a conjoint stimulus state appears which creates new patterns of expectancies. Training promotes the occurrence of these new patterns and appropriate responses. Simulation provides a suitable environment in which this can be done, and transfer of training occurs when the new expectancy patterns and responses created by the training are appropriate to the real-life situation.

Numerous factors have been examined with respect to their importance in eliciting a satisfactory transfer of training from a simulator to the real world. These include cabin and display layout and design, control responses, control feel, display noise, control-display relationship, the requirement for motion, and the nature of the external visual display.

CABIN AND DISPLAY DESIGN

Although little has been reported on the significance of ensuring a realistic cabin or cockpit representation, it appears, perhaps without justification, almost universally accepted that, wherever practicable, a cabin or cockpit should conform as closely as possible to the original, even to the extent of using actual hardware. While the importance of this is self-evident in studies involving habitability, verisimilitude is probably unnecessary in other circumstances.

For display requirements in training situations, it is necessary to simulate dynamically and with realism those displays that are critical to the operation of the vehicle concerned. For greater fidelity, flight displays should be integrated with applied motion and the external visual environment (Lybrand et al.[34]).

Hammerton [27] investigated the transfer of training occurring when a simulated task differed from the actual task only in the appearance of the display. By an ingenious technique, other relationships (e. g., the angular motion at the subject's eye and the kinematics of control movement) were maintained the same. In the one case, subjects controlled the movements of a trolley moving along a miniature railway; in the other, subjects used the same control dynamics and size of visual stimulus to control a display on the cathode ray tube. Initial transfer was very poor, with a pronounced initial decrement in performance, but recovery was very rapid and the author calculated that a time saving of 77 percent was obtained by simulation. Hammerton also makes the wry comment that there are practical situations where, if the first trial transfer is poor, the shape of the rest of the learning curve is academic. Although not comparing two actual displays, since, in fact, one was a moving model rather than a display, this study indicates that the elements of a simulated task should bear some direct resemblance to the elements of the actual task.

An additional aspect of display simulation was examined by Briggs et al.[7] who investigated the effect on transfer of training of the introduction of visual noise into a display. They showed that performance on transfer to a noisy signal was independent of the noise level in prior training trials. This finding, however, is applicable to the circumstances of the test and should not be construed to mean that, in all circumstances, performance would be independent of noise level encountered in training.

A simulator is a valuable tool for the investigation of display problems, although Rathert, Creer, and Sadoff [52] advised caution in interpretation of the results of display investigations obtained on a moving-base simulator. Using two displays—one having a director-type radar display with a line on the scope which remained parallel to the true horizon like a conventional artificial horizon, and the other having an airplane symbol which maneuvered about a fixed reference in a manner analogous to the view of an aircraft from a fixed platform in space—they compared performance in flight, on a fixed-base simulator, and on a moving-base simulator. Some difficulties arose with subjects on the moving-base simulator which the authors attributed to conflict between visual cues presented on the display and the vestibular cues presented by the simulator. In this type of situation, simulation is not merely inadequate, but can in fact introduce false cues.

CONTROL RESPONSE AND FEEL

One of the problems facing the simulator designer is the feel of the controls and their response to control action. Most of the work in this area has been done with respect to aircraft, although the principles probably apply to spacecraft. In the classic aircraft design, part of the aerodynamic forces resulting from the displacement of the control surface is fed back to the cockpit control either by reason of the linkage between the control and the control surface, or, in the case of irreversible systems, by synthetic feel forces. In the spacecraft, of course, there is no control surface in that sense, since control is by use of reaction jets. Allied with control feel are control sensitivity and required stick force. The question arises as to whether adequate transfer of training can occur when the stick feel and response on the simulator are different from those on the real-life vehicle. Muckler and Matheny,[39] with a pursuit tracking task, investigated the transfer obtained after training on different levels of control friction and found a very high positive transfer. Their results suggested that no differential effects occurred which were related to the differing friction level. Studies on varying pressures have also been carried out. Matheny et al.[36] varied control pressures with respect to the elevator on a P-1 flight simulator. Using three experimental groups, they trained one group in climbs and glides on the simulator and on an AT-6 aircraft, with control pressures in the simulator similar to those of the aircraft. A second group was similarly trained, with negligible pressure on the simulator control, and a third group had no simulator practice. The results showed no significant difference in the amount of transfer, and the authors concluded that the transfer depended more on a correspondence between the patterns of control forces than on the absolute amount of force required. In this regard, it should be noted, as Muckler et al.[40] point out in their excellent analysis of psychological variables on flight simulation, that stick feel comprises both force and displacement cues, each requiring consideration in analysis. Briggs et al.,[8] however, showed that varying the control amplitude and spring tension did not affect the transfer.

CONTROL DISPLAY RELATIONSHIPS

A similar type of problem which plagues designers is whether the relationship between the control movement, vehicle response, and subsequent display information should be identical in the simulator and the vehicle represented.

Again, much of the work in this area has been carried out with reference to tracking tasks required in aircraft. The extent to which the results are applicable to the tracking tasks and display presentation in spacecraft is open to question; however, the principles would appear to be fundamental. Rockway [55] varied the control-display ratio in a two-dimensional compensatory tracking task and demonstrated a high transfer of training regardless of whether the ratio was low, intermediate, or high. Similarly, Briggs [9] investigated the use of simplified systems, in which the aircraft transfer function used in the representation was simplified from a doubly integrated acceleration system to a singly integrated velocity system. Training on the task in which the aircraft transfer function was represented by a velocity system was followed by a performance test on the task where the aircraft transfer function was represented by an acceleration system. Performance on the latter system was compared with the performance of a control group who had trained in the acceleration system throughout. The proficiency of the test group using the acceleration system was found to be a function of their amount of training on the velocity system. The control group, who had trained throughout on the acceleration system, had a higher level of performance than the test group. The rate of acquisition by the test group of the level achieved by the control group was also found to be a function of their training on the velocity system. Thus, it would appear that moderate variations in the control display relationships have little effect on transfer of training, and also that satisfactory training may be achieved by using simplified display systems which do not have a direct relationship to the task.

MOTION SIMULATION

The problem of adding satisfactory motion to flight simulation is one that has beset design engineers considerably, although were it not such a severe and expensive design engineering problem, there would probably be little argument as to its value. While much has been written on the requirements for motion in aircraft flight simulation, little has been presented on the necessity for motion cues in a space-flight simulation. It has been largely taken for granted that in space-flight simulation motion will be provided where it is applicable. The questions that arise in both are, Where is it applicable and how faithful should be the representation? Complete fidelity is obviously impracticable, if not impossible, because of the inability to provide for translation of masses and linear acceleration to any appreciable extent. In point of fact, the use of the word "motion" is misleading, since, apart from relative velocities perceived by vision, the body cannot perceive motion per se, but is sensitive only to higher derivatives, such as acceleration and jolt. Thus, in regard to body response, it is the rate of change of motion that must be simulated. This makes the problem both easier and more difficult—easier since it is unnecessary to maintain the motion once the acceleration has occurred, and more difficult since maintenance of prolonged linear acceleration is difficult, if not impossible, to achieve within the constraints of a flight simulator. For some types of task, for example, landing or docking tasks, a visual representation of relative velocities may also be needed.

From the point of view of perceptual equivalence, however, advantage can be taken of the fact that the body is insensitive to motion or velocity per se. Using the technique of "wash-out circuitry," a motion can be applied to a simulator at a rate of change and for a duration that is readily perceptible to the pilot and representative of the motion being simulated. The motion is thereafter removed or "washed-out" at a rate below the pilot's vestibular and proprioceptive threshold of sensitivity, although its apparent effects are continued on appropriate instruments. An illusion of continued motion is provided. Such an illusion, of course, does not produce the physiological effect of sustained motion, or coriolis acceleration, although buffeting and moderate intensity impacts can be reproduced.

As noted, most of the work justifying the requirement for motion in flight simulation has been done with respect to aircraft, or more precisely with respect to its effect on aircraft pilots. Muckler et al.,[40] in their comprehensive review, state:

> A considerable part of the total pilot's task involves performance of continuous feedback skills, or tracking tasks, in which he is continuously attempting to null the difference between an indicated instrument reading (the index of actual performance) and some desired instrument setting (the index of desired performance). These tasks vary greatly in their complexity. The pilot may be primarily concerned with nulling the error of a single index, as in the attack portion of the intercept, or he may be dealing with a number of indices, all of which he is attempting to maintain at desired readings. The ability of the pilot to execute these tasks will be determined to a great extent by the performance characteristics of the aircraft. . . . The handling characteristics of an aircraft are determined largely by stability and control characteristics, and these in turn reflect the dynamic response of the aircraft.

While written with respect to aircraft, this applies with little modification to spacecraft, particularly with reference to launch, reentry, and controlled landing situations, and indicates the significance of vehicle motion in affecting control performance. In the weightless or reduced gravity states, still further complications will be added.

Simulation of flight motion initially requires specification of the modes of motion. An aircraft or a space vehicle can move in six degrees of freedom. However, largely on the basis of pilot preference, it is customary to design most of the motion in the pitch plane. Neiswander and Armstrong, quoted by Muckler et al.,[40] on the basis of literature review and their own experimentation, concluded that if motion is to be incorporated in a simulator, it should include no yaw freedom, a large range of pitch angle, restricted roll characteristics, and limited translational motion.

Specific motions, for example, longitudinal or lateral, can be analyzed aerodynamically with respect to the characteristic transient oscillations that occur following disturbance from an equilibrium state, either voluntarily or because of turbulence. A relatively short-period, highly damped oscillation (the short-period mode) occurs along with less-damped, long-period, or phugoid mode oscillations. Varying short-period mode oscillations can be simulated on a variable stability aircraft, and the subjective response of pilots can be measured using a pilot opinion rating scale. Such a test was carried out by Chalk,[17] where he used the following pilot-opinion rating scale:

(1) Optimum: Best all around; combines best precision and greatest comfort.

(2) Acceptable good: Better than acceptable, but could be improved; for example, comfortable but not most precise.

(3) Acceptable: Mission could be accomplished reasonably well, but would require considerable pilot effort or attention.

(4) Acceptable poor: Airplane safe to fly, but extent of pilot effort or attention required would reduce effectiveness.

(5) Unacceptable: Pilot effort or attention required to the extent that accomplishment of mission doubtful; airplane unsafe if pilot's attention required for other activities.

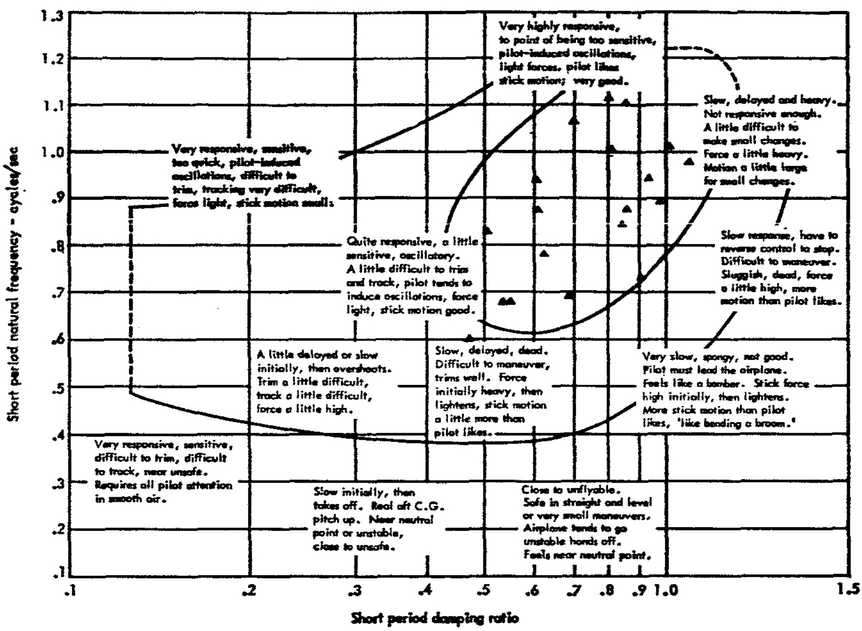


Figure 3.—Vehicle dynamic response. (Source: Webb [71])

The results of the study by Chalk are quoted by Webb [71] and are represented in figure 3. The curves denote approximate boundaries of pilot opinion as measured on the rating scale. The inner curve bounds the acceptable region; the outer curve bounds the acceptable-poor and unacceptable regions. The data points show the "best tested" configurations. The comments are summaries of prevalent pilot remarks in various regions of natural frequency plotted against damping ratio.

The flight Euler equations can be incorporated into computer equations and used in turn to provide signals for moving-base simulators. Responses to simulator flight, variable stability aircraft flight, and actual aircraft flight can then be compared, and the requirement for motion in a simulator can be evaluated.

Brown and Johnson,[10] using two experienced pilots on the NASA normal acceleration and pitch simulator, investigated, inter alia, the effects of motion simulation on aircraft controllability. The simulator could pitch and move vertically, the motions being those associated with the short-period mode. Differences in accuracy of performance measured with and without pitching motion were very small for one pilot and negligible for the other, although the performance actions were smoother with added simulator motion. Consequently, pitching cues were not considered important where the oscillations encountered were within the acceptable range of the short-period mode.

Rathert, Creer, and Douvillier [51] and Rathert, Creer, and Sadoff [52] reported more comprehensive studies to determine the requirement for motion. In a landing approach problem, using an ILS display, they noted that the critical information required is the rate of sink. This can be provided by visual instruments alone, with no motion required. They also investigated longitudinal dynamics, using for reference a Cornell Aeronautical Laboratory study designating regions where short-period frequency and damping were subjectively evaluated by pilots as good, acceptable, poor, and unacceptable. In the good region, where short-period frequencies are moderate, that is, at about 0.6 cps, with good damping, fixed-base simulation was found to be adequate and realistic. At short-period frequencies above 0.6 cps, the fixed-base simulator was found to be easier to fly than the aircraft and unrealistic in feel. In this region, there is a rapid response to control, with feedback motions which become increasingly difficult to cope with as frequency increases and damping deteriorates. In other words, where there is a rapidly responding control and very high control sensitivity, or low stick force per g, the pilot-control-aircraft combination becomes unstable with pilot-induced oscillation. A simulator for these circumstances requires motion cues.

They also noted that lateral dynamics are influenced by roll-damping and roll-control power. In the region representative of normal aircraft operation, no difference in performance was observed between fixed or motion simulators and the aircraft. At higher rolling acceleration, however, the fixed simulator was found to be unrealistic, and at very low rolling rates, because of the anticipation provided by the motion cues, the motion simulator was found easier to fly than the fixed simulator.

Sadoff and Harper [59] also undertook comparisons of fixed-base and moving-base simulation, with respect to the general handling qualities of conventional V/STOL and reentry type aircraft. In general, they found that fixed-base simulation was adequate except for those regions of dynamic oscillation near the boundary between what was subjectively acceptable and what was unacceptable. They also found that motion cues were essential for realistic assessment of abrupt damper failures at high, short-period frequencies. For lateral directional control, such as that found in reentry of the X-15 with the roll damper inoperative or during low speed in a STOL aircraft or high-performance jet aircraft, motion cues were considered useful but secondary.

In a further study, Sadoff [58] used the Johnsville centrifuge as a flight simulator, but in a manner designed to reduce coriolis effects. He investigated five situations, three involving sudden reduction in pitch damping and two involving sudden reductions in static stability. In four of the five situations, a significant adverse effect in the pilot's ability to adapt to the failures was noted. One situation, failure of a static stability augmenter, showed the beneficial effects of motion. Despite the possible coriolis interference, these situations are considered by Sadoff to be true representations of actual responses. He states: "These results suggest that simulator motions are generally required for a realistic assessment of the pilots' ability to cope with stability augmentation failures."

In a somewhat different field, Fedderson [22] simulated a hovering helicopter statically and in a six-degree-of-freedom simulator. After each subject reached an asymptotic level in his training, he was given six 2-minute hovering trials in a helicopter and then transferred to the opposite condition (i. e., static or moving) from that which he had in training. The group with motion cues learned to hover faster, and when transferred to the helicopter performed better initially in the air than the group trained in the static simulator. The difference, however, disappeared by the end of the 12-minute flying session. Because the difference disappeared so rapidly, Fedderson considered that use of a motion simulator could not be justified.

In still another field, Buckhout et al.[12] compared the effect of training for high-speed, low-level flight on a fixed-base simulator and under applied turbulent conditions. After initial false starts, they devised a protocol whereby a control group was trained on a static simulator with a one-dimensional, outside-in compensatory tracking task, while other groups were trained under static conditions with instrument "jiggle," or under conditions of 100 percent turbulence. Results showed that the subjects trained under motion conditions had significantly higher rms error scores during training trials, but that they performed better in a simulated criterion flight task than did the subjects trained under static conditions. No significant difference was observed between the two motion groups. In addition, the frequency of "crashes" and "penetrations" during the criterion test was markedly higher for the statically trained group than for either of the motion groups. They conclude, in general, that "Simulated motion during the learning of tracking skills contributes to more effective performance in a criterion test situation in which motion cues play an important role. . . . Performance on a procedural task (reaction time measures) did not differ significantly as a function of the type of training received."

In confirmation of the effect of procedural tasks, Wilcoxin and Davy [73] found that rough-air simulation had no effect on transfer from simulator to aircraft in the performance of basic instrument and radio range procedures training, although the students believed it added realism.

Douvillier et al.[20] also undertook studies comparing tracking in flight, on a fixed-base simulator, and on a moving-base simulator and concluded that the results from the moving-base simulator resembled the results from actual flight much more than did those from the fixed-base simulator.

Thus, as far as aircraft are concerned, the consensus would seem to be that motion cues are necessary in those situations where they contribute to improved control of the vehicle or where they interfere with satisfactory performance. There appears to be no definite evidence, however, as to whether these motions should be part of a complex integrated type simulator or whether an adequate transfer of training can be provided separately on a simpler simulator designed to present an appropriate task or tasks under motion.

With respect to motion in space simulators, the same general rule would seem to apply. Young and Barker [76] compared performance on a vehicle with a low lift-to-drag ratio entering the earth's atmosphere. Pilots used an on-off reaction control and damping system for regulating the vehicle's roll angle. Proportional reaction damping systems were used for stabilizing the vehicle in pitch and yaw. Little difference was noted in the time histories of typical entries of the fixed-base and moving simulators. However, pilots showed a preference for the moving simulator because they believed the cues provided by the angular motion aided them in performing required entry maneuvers. It was their opinion that, with the moving simulator, the training period required to receive proficiency was reduced. Urmer and Jones [69] draw attention to an important point in this regard and suggest that in full simulation of motion on the ground a pilot may learn to expect vestibular and other proprioceptive feedback from the gravitational resultant. These cues, of course, will be absent in the null gravity situation of space. Because of this, it may be better to train without added motion cues, relying on instruments and, if applicable, an exterior visual display.

EXTERNAL VISUAL SIMULATION

There is no doubt that perception of the visual world provides the greatest of all the sensory cues for orientation and vehicular control. Because of optical and engineering complexities, however, it is only in recent years that attempts have been made to provide simulation of the external visual environment.

As with other simulation modalities, simulation simply for the sake of verisimilitude is of dubious value, and a careful task analysis is required to determine what factors within the environment require simulation. Woodson [74] analyzes the components of a lunar mission as prelaunch, launch, injection into orbit, earth orbit, rendezvous, docking, injection into circumlunar orbit, midcourse navigation, injection into lunar orbit, lunar orbit navigation, injection of lunar excursion module (LEM) into landing orbit, LEM landing orbit navigation, lunar approach, lunar landing, LEM launch from moon, rendezvous and docking of LEM with spacecraft, injection into return orbit, midcourse navigation, injection into earth landing path, atmospheric penetration, guidance to landing site, approach, and landing. He points out that each of these phases requires some difference in the appropriate external visual environment. It is apparent, however, that there is no need to recreate the entire visual world in any given area; nor is there a requirement to provide visual simulation for all aspects of a space mission, when for a large part of any mission no external vision is required.

Thus, in the type of mission analyzed by Woodson, many of the phases have little or no requirement for an external vision display, except for the purpose of verisimilitude. Facilities are required, however, for presentation of displays governing terrestrial, celestial, and lunar or planetary observation, rendezvous and docking, and terrestrial or other landing. Where observation is the fundamental requirement, we are concerned with use of vision for detection, recognition, and identification; whereas in the situations of rendezvous, docking, and landing, we are also concerned with the use of vision for external orientation and the monitoring of vehicle control and extravehicular activity. This latter requirement entails a visual evaluation of attitude, distance, velocity, and acceleration.

As a general statement of visual simulation needs, Roscoe (personal communication) suggests that the external field of view should include the following:

(1) The celestial sphere

(2) Point source moving objects, such as planets, distant vehicles, or other targets

(3) Distant but resolvable planetary or lunar surfaces (phenomenally two dimensional)

(4) Proximal planetary or lunar terrain (phenomenally three dimensional)

(5) Resolvable moving objects such as surface, airborne or spaceborne vehicles, or other targets (phenomenally either two or three dimensional, depending on range)

The internal field of view should include vehicle interiors, such as cockpits and other crew stations, their displays and controls, and the ambient illumination thereof.

As in other forms of manned simulation, while operational and psychophysiological research demand physical fidelity and reproduction of critical parameters, the objectives of training simulators provide a prime example of the usefulness of perceptual fidelity. In this connection, several factors may be considered.

Assuming the existence of windows, periscopes, or the like, an important consideration is angle of view. Molnar and Lybrand [38] state, somewhat arbitrarily, that there should be a horizontal visual angle of 120°, while Aronson [4] claims that 25° to 30° is sufficient to give full cockpit vision performance. It is probably better stated, however, that the angle of vision should be adequate to provide a field of vision comparable to that obtained during reasonable head movement of a vehicle operator and, in any event, not less than 30° with suitable peripheral masking. Equally, the field must be such that realistic portions of it can be observed by another vehicle occupant in a different position without optical problems induced by motion parallax.

Field luminance also requires some attention. Buddenhagen and Wolpin,[13] in their comprehensive study of visual simulation, note that the range of luminance of the Earth's surface viewed from outside the atmosphere rises from less than 1 lambert to approximately 9.4 lamberts; the luminance of Venus is approximately twice that of Earth, whereas the Sun is greater by a factor of 100,000.

Simulation of a range of luminance of this order is virtually impossible. However, while visual acuity and intensity discrimination improve as a function of luminance, the improvements tend to become asymptotic at about 100 millilamberts. Thus, in terms of perceptual fidelity, for normal training purposes, the maximum required luminance will be found at 100 millilamberts. This in turn will lead to development of a relative luminance scale. A scale of this type, however, requires experimental validation, since relative brightness, which is a subjective appreciation, does not bear a direct relationship to relative luminance. Techniques of preparing this kind of scale are discussed by Buddenhagen and Wolpin.[13]

Contrast is another factor to be considered. Threshold contrast is the least contrast required for an object to be detected against its background, and in terms of brightness may be represented by the term dB/B, where B is the background brightness and dB the increment of brightness. Subjectively, the threshold contrast does not change significantly above a background luminance of 0.1 millilambert. Since the space background luminance is considerably lower than this value, care is required in simulation to ensure adequate contrast.

Dependent upon background luminance, luminance contrast, and in addition, duration of exposure, is visual acuity. This is defined as the reciprocal of the resolving power of the human eye. Buddenhagen and Wolpin [13] define three aspects of visual acuity, each of which requires consideration in simulation. They describe them as follows, citing their sources:

> Minimum detectable acuity refers to the ability to detect a point light source. The chief determinant of such an ability is the source luminance. The minimum illumination of the eye, yielding 50 percent probability of detection, is 10^{-10} foot-candles at the eye. A light source subtending a visual angle of less than 10 seconds of arc is sufficiently small to be defined as a point source. All of the stars and many planets, as viewed from the earth or earth orbits, are then point sources. Therefore, the basic defining detection thresholds, as a function of luminance and level of adaptation of the eye, can be applied in developing a simulation situation which possesses perceptual fidelity.
>
> Minimum perceptible acuity is a measure of the smallest resolvable angle. The major parameter affecting the size of the visual angle detected is the background luminance. Under ideal conditions a fine wire subtending a visual angle of 0.43 second can be detected 75 percent of the time, as can a dark square subtending 14 seconds of arc. Dark bars on a light background yield a minimum of 60 seconds of arc.
>
> Minimum distinguishable acuity, or "form sense," is the ability to

detect irregularities in the form, shape, or contour of an object. The major parameters affecting this function are object luminance and luminance contrast. Measured by laboratory techniques, a nominal minimum of 40 seconds of arc is obtained. [They do not specify the particular shapes of objects, if any, to which this statement is applicable.]

So far we have been concerned with visual factors underlying simulation for observation, whether of terrain or target. Recognition and identification of terrain or target, however, require training with appropriate models incorporated into the visual displays.

In considering the additional visual factors involved in rendezvous, docking, and landing, it is well to note that fundamentally the same type of visual information is needed in each—only the source differs. The operator must know the attitude of his vehicle with respect to the target, the distance between vehicle and target, the rate of change of distance (velocity), and the rate of change of velocity (acceleration).

The visual determination of distance or depth is a highly complex procedure utilizing cues from a large number of sources, each of which has to be considered in providing simulation.

For short-distance judgments, the most useful of these cues results from the stereoscopy produced by binocular vision, in which the difference in distance between two points is perceived by comparing the size of the two convergence angles between each of the points and each of the eyes. As the angular difference approaches 30 seconds, the stereoscopic resolving power becomes zero. Similarly, as the convergence angle approaches 30 seconds, the resolving power becomes zero. With an interocular distance of 65 mm, this range is found to be about 500 yards (Neuberger [42]). Thus for an object beyond 500 yards, stereoscopic vision provides no additional information. For most practical purposes, stereopsis is of real value only for distance judgments up to about 30 feet.

Monocular cues provide a wide variety of useful evaluations, particularly for distances beyond 30 feet. These are discussed in detail by Pfeiffer et al.[47] as an extension of the work on the geometry of perspective by Calvert.[15] A summary of this discussion is given in the following paragraphs.

Texture

The texture of referent surfaces provides a major clue to visual orientation. Carel (personal communication) points out that without a visually resolvable texture, there is no visible surface. At the same time, textural elements can be manipulated to achieve perceptual fidelity, and it would not appear necessary to reproduce the actual texture of the perceived environment. In work carried out by Carel's group, also discussed by Aronson,[4] it was shown that random groupings of light and dark squares (whose sizes and cluster distribution change with altitude) were adequate to produce an appropriate impression of texture. The implication is that simulators requiring external displays, particularly for training purposes, may forego, with considerable advantage, the necessity of generating a picture that is a literal copy of the world.

Carel states that the only objects which need to be visually simulated (in terms of texture) are the visual surfaces that represent the referent surfaces to which the vehicle is flown and also the visual object that represents the terminal goal of the vehicle, for example, a runway or a landing pad. The same textural requirement is important in the design of real objects to which visual orientation must be made, for example, a rendezvous vehicle.

It is not the purpose here to do more than emphasize the significance of texture. Further reference will be found in

Gibson[25] and Carel.[16] A point of caution remains—if the external visual display is provided by way of a television viewing screen with a local texture, the observer may accommodate and converge on the screen. A conflict of information may result between the physiologic cues and the pattern cues.

Linear perspective

Linear perspective is the apparent convergence of parallel lines and is a special case of texture perspective where the edges of the texture elements are objectively parallel like railroad tracks and appear to converge on a horizon vanishing point. Linear perspective may serve as a cue for altitude as well as distance, since the greater the altitude at which the pilot is approaching the runway or landing area, the less the lines will appear to converge. External visual systems using patterns of intersecting and converging lines have been used with considerable success in the design of take-off and landing flight simulators (Barnes[5] and Xhignessee[75]), and might well have application in space flight simulators where verisimilitude of terrain or target is not required.

Shape

Evaluation of the shape of terrain or target features is another cue and another example of the use of linear perspective. Apparent distortion of known shape provides, with experience, a cue to the distance between the viewer and the feature observed.

Interposition

Interposition is the location of near objects in front of, or on top of, far objects. If an object is partially hidden by another object, the former must of necessity be behind the latter. This cue has particular significance when related to the horizon. If an object appears to an observer to intersect or rise above the horizon, then the observer is at the same altitude or below the object.

Size of objects

The apparent size of objects of known size provides a relative cue for distance, since the retinal image of an object varies inversely with the distance from the object. Similarly, resolution of general detail indicates distance. The closer one is to an object or area, the greater the resolution. When using television projectors to provide the simulation, problems of resolution may arise, since television projectors are commonly limited in the detail of their resolution. Detail can be extremely important for object recognition or identification, as, for example, in earth observation or target identification.

Motion parallax

The phenomenon of motion parallax or motion perspective provides a valuable cue to distance and is important in providing information on the velocity vector. The term is applied to the naturally occurring situation, whereby distant objects pass through a field of vision in a direction opposite to that in which the observer is going. The apparent velocities are inversely proportional to the distances.

Accommodation and convergence

Visual accommodation, or the capacity of the eye to change its focus accompanied by convergence of the two eyes, is a valuable cue to the determination of short distance, but is applicable only to distances of less than 20 feet. A useful practical point, however, arises in this connection, in that with presentations requiring projection, location of the screen 20 feet or more from the viewer reduces the likelihood of providing artificial cues of screen texture, etc. Perhaps, however, this precaution is less important than has been considered, since, as Aronson [4] notes, screens, particularly spherical screens, have been placed at a radius of 10 feet from the observer without apparent problems.

Aerial perspective

Aerial perspective is a rather poor name which is applied to haziness of outline of objects which progresses as their distance from the eye increases. Although a useful qualitative cue, it is difficult to simulate, but deserves consideration as part of the total visual pattern and as a phenomenon which interferes with accurate identification and recognition.

Velocity and acceleration

In a rendezvous and docking situation in space, velocity can be appreciated visually only as a rate of change of size of the target or of increase in resolution, while acceleration is noted as a rate of rate of change. The landing situation, however, whether terrestrial or lunar, provides other cues related to the apparent behavior of the immediate visual environment. These have been analyzed by Calvert [15] and developed by Pfeiffer et al.[47] Calvert defines the X-point as the point at which a vehicle is aimed at a given instant; that is, the point at which there is no apparent movement of the external visual environment. All other points appear to move away from the X-point out of the field of vision at a rate which is a function of the velocity of the aircraft toward, and the distance from, the X-point. The effect is to form "streamers," the tangents of which meet at the X-point. The angular distance of X below the horizon provides an assessment of the rate of closure with the ground. The angular distance of X from the horizon, or the H-distance, provides the rate of closure with the vertical plane through the center line. The movement of X perpendicular to and parallel with the horizon provides a rate of rate of change (acceleration) in the vertical and horizontal planes. Provided that some form of texture, abstract and real, is available in the simulated display, these cues, of course, are inherently present and unconsciously used by the operator.

Carel (personal communication) points out, with some justification, that consideration of the standard textbook list of visual cues (interposition, linear perspective, etc.) as a guideline for the design of external visual displays is probably an unrewarding approach. He decries the belief that the pilot analyzes the visual world in terms of attitude, distance, velocity, and acceleration, and suggests rather that the pilot operate in a holistic fashion. What he learns is the vehicle dynamics, and he becomes adept at predicting the behavior of the vehicle in the visual space he can see. With experience, he could fly the vehicle and still know nothing, in the conventional sense, of his distance, velocity, and acceleration. Consequently, a completely abstract display in the form of an array of surfaces (ground, launching pad, etc.) would form a microcosm for the pilot with respect to which he could fly, provided that both dynamic and static scaling were uniform. Thus, a visual display should be conceived as a whole pattern.

While this approach is no doubt valid, it must be realized that in point of fact the pilot in perceiving his dynamic visual environment is, in one way or another, making unconscious analyses in physical terms although he is not interpreting them as such. Consequently, there is justification for analyzing the simulated environment in physical terms to assist in determining design criteria.

The question of color in visual simulation remains for discussion. Aronson [4] suggests that, except for visual reconnaissance, the use of color should be limited in providing command information (e. g., green boundary lights and red obstruction lights). Buddenhagen and Wolpin [13] note that the presence of color in the visual field tends to increase contrast and decrease the threshold of recognition and detection. Color cues are important primarily in the landing phases of a mission, selection of landing site, and final maneuvers, although they may be useful in identifying celestial objects and light sources. In general, it would appear that color presentations are useful but not essential.

COMPONENTS OF A REPRESENTATIVE VISUAL SIMULATOR

By way of example, representative elements of a typical visual simulation facility are listed as follows (Roscoe, personal communication):

(1) Work stations, including displays and controls

(2) External visual environments

Planetarium to produce celestial sphere

Models, television systems, film strip imagery viewers, and projectors to produce distant two-dimensional resolvable earth or moon representations

Continuous moving belt models, belt-drive system, and servo-driven television system to produce proximal three-dimensional terrain

Gimballed spot projectors and collimated cathode ray tubes to produce distant point-source moving objects

Gimballed translating models, servo-driven television and optical systems, to produce proximal three-dimensional moving objects

(3) Internal visual environment

Film transports, flying spot scanners, scan and sweep generators, noise generators, alphanumeric and symbol generators, target generators, servo followers, digital servos, and shaft encoders to generate inputs to various displays

CHAPTER 4

USE OF MANNED SIMULATORS

HUMAN FACTORS STUDIES

In the human engineering field, simulators, generally of the simple mock-up variety, have for years been used in determining cabin design criteria, instrument and indicator display and location, and control design and location. Habitability studies, such as those reported by Steinkamp,[66] using the SAM space cabin simulator, may require much more complex simulation with provision of a representative sealed cabin and controlled atmosphere, while the development of procedures and requirements for a given space mission may entail the use of several different types of simulators. Clausen [19] illustrates the complexity of simulation entailed in developing procedures and requirements for the Gemini mission. Simulation studies ranged from simple electronic devices, duplicating display light sequences during the launch phase, to complex integrated mission simulation of the docking phase. A simulated crew station was constructed to permit real-time evaluation of guidance and control systems. This facility was used to evaluate hand controllers, displays, and attitude control system configurations, and was expanded to include optical systems. Many of the simulations incorporated operational equipment and took place in a high-gravity environment.

Grodsky and Bryant [26] also examined the uses of simulators and showed that by using a complex mission simulator with man as a functioning element in the overall system, an evaluation can be made, among other things, of crew performance and the interaction of the man-machine environment with respect to crew status during the mission, the appropriateness of information displays and controls, vehicle dynamics under simulated conditions, and task complexity and proper sequencing.

EVALUATION OF MAN'S CAPACITIES

In considering the use of simulators for the evaluation of man's capacities, it is necessary to emphasize that a situation, environment, or task can be simulated in a valid manner only to the extent that its parameters are known; as a corollary to this statement, a simulator will provide the solution to a problem only if the elements of the solution reside in the simulation. Thus, a simulator can be used as an environmental stressor when the nature of the required stress is known and can be represented, as in using a centrifuge to provide sustained accelerative stress. Responses measured under such circumstances will provide valid data if the measurement techniques are valid. A simulator, however, regardless of how sophisticated, cannot be used to obtain valid measures of the human response to the complexities of a space environment unless the actual parameters of that environment are fully known and those that are significant are fully represented within the simulation.

Redgrave [53] points out that, since not all significant characteristics of the situation to be simulated are necessarily known to the designer, the simulation may be incomplete. In addition, several significant factors cannot be simulated and emotional disturbances are largely lacking. Thus, a designer may have difficulty in selecting the best factors to simulate for the most desirable results; consequently, any circumstances will be measures of responses to a simulated world and can be applied to the real-world situation only to the extent that the simulation approaches actuality. The less known about the actuality, the less can it be simulated and the less valid the application of the resulting data. This warning is even more apposite when the environment is simulated in terms of perceptual equivalence, since in such a case only an illusion of the environment is in fact simulated.

Much of the data obtained on man's physiological and psychological capacities and limitations and his performance and proficiency in stressful and non-stressful situations has been obtained on simulators of one form or another, such as altitude chambers, centrifuges, rocket sleds, performance consoles, treadmills, shake-tables, etc.; and such data are acceptable since the parameters of the strain and stressors are known. But when an attempt is made to determine the interaction of the stresses by the nature of the human response and to relate that in turn to the interaction of the stressors, the circular reasoning becomes evident.

DURATION OF SIMULATION

To predict the effects of long-duration stress from a short-duration simulation poses considerable difficulties, and, in this connection, it is perhaps wise to examine briefly some aspects of the human stress response. When the body is exposed to a mild stimulus, it reacts to that stimulus by modifying its physiological and psychological outputs. Where the intensity or the duration of the stimulus exceeds the body's capacity to modify its outputs at the level of function, energy-consuming compensatory changes occur within the body. These compensatory changes are manifested as measurable alterations in physiological function and may be regarded as evidence of strain from which the existence of a causative stress may be inferred. Thus, human stress, as opposed to the engineering concept, is observed to occur only when its effects are manifested, latently or overtly, as symptoms and signs indicative of strain. With further increase in intensity or duration, still further compensatory changes take place until no reserves are left, at which point psychological and/or physiological failure will occur.

It will be noted, however, that where a stressful stimulus is maintained at the same level for a prolonged period, a highly motivated operator will maintain a high level of performance despite the occurrence of progressive compensatory changes until just prior to his physiological failure. This principle is illustrated in figure 4. The question that besets investigators in this

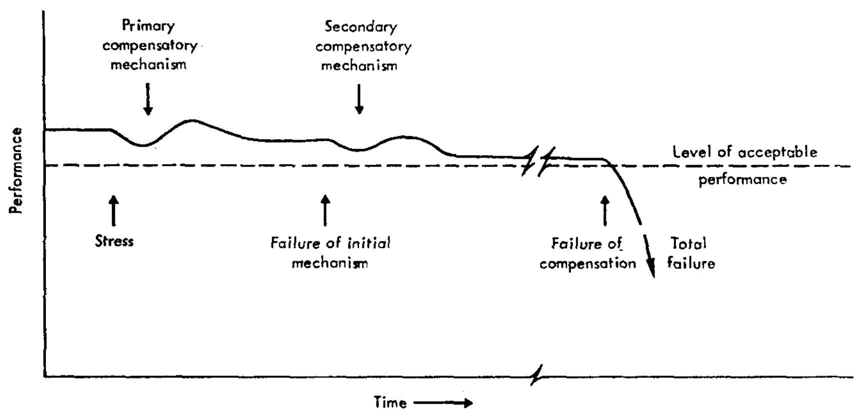


Figure 4.—Performance under prolonged stress.

connection is how long must one simulate a stressful situation in which performance is adequately maintained before one can predict the point at which performance will fail. To put it in more concrete terms, for a space mission of 12 months duration, the question is, how long must the appropriate simulated mission be to ensure the adequate reliability of man within the space environment? The answer is hard to come by since predictive data of this nature do not appear to be available. For the short-duration space flights completed and currently anticipated, it has been the rightful practice to simulate them in their entirety. In fact, some authorities (Schwichtenberg, personal communication) suggest that, using the engineering concept of a safety factor, the duration of a simulated mission should exceed the duration of a real mission in order to ensure a greater probability of reliability in the latter.

While this concept is no doubt valid at this stage of space exploration, it of course becomes less and less feasible as the durations of missions increase; and, in fact, with durations of 3 to 6 months, it becomes barely feasible to simulate the full duration of a mission. How long the duration of simulation should be is just not known at this time. It seems very probable that the relationship between length of mission and optimum length of simulation is not linear. It might well be expressed in the form shown in figure 5, where the length of the mission is plotted against the ratio of simulation duration to mission duration. Thus, a mission of unit length would be assigned a 2:1 ratio and other durations extrapolated accordingly. Unfortunately, there are no numbers to apply to the plot, and, in particular, the length of the arbitrary "unit mission" is not known, although the feasible limit would seem to be about 3 to 6 months. However, until numbers can be applied to this plot, it is necessary that either mission durations be reproduced in their entirety, or that a new approach to simulation for long-duration missions be developed, whereby no attempt is made to simulate the full duration of a space mission in all its aspects. In the latter case, by the sheer constraints of economy of time and money, it will be necessary to depart from the principle of validating man and machine reliability in situ, as it were.

It would not be reasonable to tie up astronauts and complex simulators for many months. Instead, in the study of long-

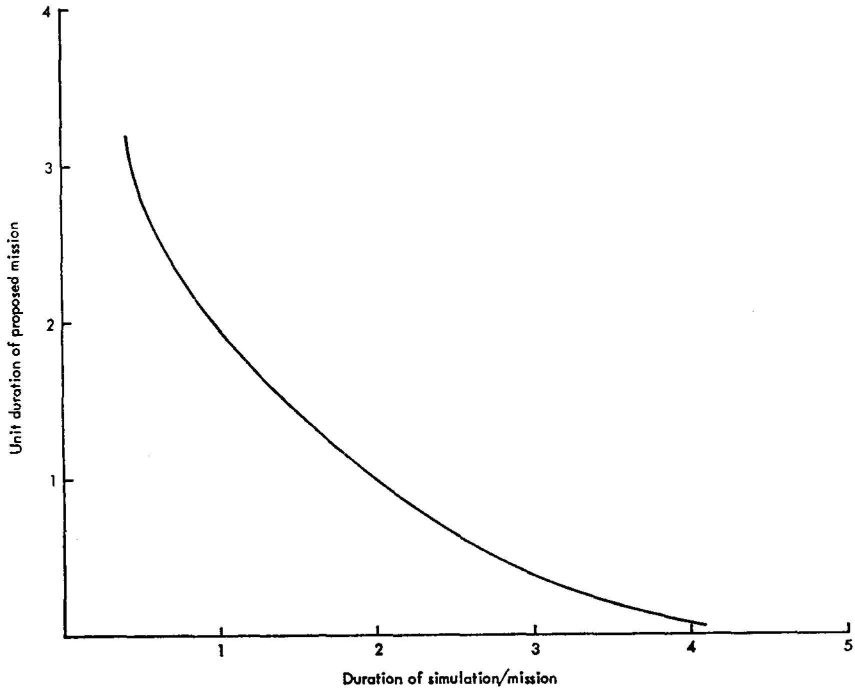


Figure 5.—Relationships between duration of proposed mission and duration of required simulation.

duration missions, it will be necessary to deemphasize the man-mission orientation that has been so much a part of manned space investigations and return to the investigations of man and representative man-machine systems. When man's capacities, limitations, and performance capabilities are better known, it will be possible to determine the extent of his participation in a given mission. These responses to carefully controlled single and multiple stresses over prolonged durations, using carefully graded performance tests, can be undertaken on "average man" subjects with relatively simple simulators and can provide a body of knowledge from which it will be possible to calculate, with reasonable reliability, the probability of successful completion of a prolonged mission.

A safety factor will lie in the reasonable assumption that the selection procedures used in choosing astronauts will allow selection of individuals whose capacities and tolerances are greater than those of the "average man."

TRAINING AND SELECTION

As discussed in the section dealing with fidelity and transfer of training, the use of simulators for training purposes is not without problems. However, there is no doubt that it is this field in which the simulator makes one of its greatest contributions. In addition, through the proper use of simulators in manned system design and development, the training required in system operation can be greatly reduced. Simulators can be used in the development of training programs; in the teaching of procedures, techniques, and management methods; in determining and providing training in special areas; and, when combined with appropriate measurement methods, in establishing crew proficiency. Perhaps most important, a simulator can be used for providing perceptual experience of, and familiarization with, a given vehicle and space environment.

It must be emphasized, however, that verification of the utility of a simulator, both for the suitability of its design as a trainer and the choice of procedures possible in it, can only come by comparing simulator performance to space performance.

With regard to the philosophy of training, one must emphasize the importance of breadth and flexibility. Rigid procedural training is only of value in mastering rigid procedures. One of the most important aims of training is to teach the operator in such a way that he will readily transfer what he learns to as wide a range of related situations and equipment as may be required. In this regard Szafran [67] in a paper to the Warsaw Congress stated: "The vital phases of the high-grade skills in advanced aviation should always be inculcated in a setting which permits, indeed encourages, modification of strategy as well as of tactics in the face of varying task conditions and error tolerances."

In a personal communication, Szafran points out that, while the experience of space flight must be considered a unique whole, it does not necessarily follow that the component parts need to be simulated in entirety. In fact, to do so might well produce a minimum transfer, since the concealment of vital differences is thus made more complete. The main principle in separating skills should be to split the major task into a number of elementary components, each of which must be so simple and the objectives so constant and definite that the knowledge of results is clear and unambiguous. Much simpler equipment would be required to undertake the training than is found in the integrated mission simulator. Successful training under the circumstances would depend on the following:

(1) Choice of component tasks.

(2) Order of presentation of tasks: A progressive training would be required whereby early basic tasks would be phased out as new tasks are introduced, and these in turn would be replaced by still further tasks.

(3) Duration of training: Training must be maintained until the response is automatic, particularly in the case of the basic skills.

(4) Emphasis on temporal and spatial relationships: Whether in display, control, or both, changes in temporal and spatial relationships provide the greatest difficulty in the achievement of adequate transfer of training and should receive particular emphasis.

(5) Trend of difficulty: Since a higher positive transfer tends to result from a difficult to an easy task than from an easy to a difficult task, component training problems should be set wherever possible at a manageable but high level of difficulty.

One area of usefulness that has received perhaps less attention is that of astronaut selection. It is true that in the past, simulators, in particular, environmental simulators such as stress generators, have been used in selection procedures, and no doubt achieve a useful purpose. However, with the increasing requirement for astronauts, and when they are no longer being drawn solely from the ranks of test-pilots whose response to stress is somewhat more known, it may be necessary to develop a concept of progressive selection and elimination. In such a concept, after initial selection procedures similar to those currently employed, the astronaut candidates would be permitted to begin a training and proficiency testing program leading to final selection and elimination. The use of simulators of many types, including the complex mission simulators, might well play a part in such a program.

TYPES OF SIMULATORS

From the preceding discussions, it is evident that to accomplish the purposes of selection and training and to investigate the man-machine-environment interfaces, several different types of simulators are required. Three basic types might be recognized, although the dividing lines are somewhat hazy; they are the integrated mission simulator, the part-task simulator, and the environmental simulator. A system simulator can also be recognized which includes a mission simulator as a component, along with a representation of the supporting ground environment.

Integrated mission simulator

In the integrated mission simulator, an attempt is made to provide, as an integrated unit, a realistic representation of a space vehicle with its internal and external environment. To encompass the scope of varied requirements, the ideal integrated mission simulator would need to provide a cabin with crew stations and internal design to match a given class of space vehicles, with operating instruments, switches, and displays responsive to the simulated external environment and operator inputs; the cabin would be required to be mounted on a moving base in six degrees of freedom, capable of responding to externally simulated forces and operator controls; "wash-out" circuitry would be needed to provide perceptual equivalence of motion cues; an external non-programmed visual environment would be available as required to match the mission as viewed through windows, port-holes, or periscopes and to respond realistically to match the vehicular motion; the internal environment would be controllable in terms of atmospheric composition, pressure, temperature, humidity, and noise, with appropriate response of instrumentation and displays; the cabin simulator would need to be located within a space environmental chamber with a capacity for controlling the external environment; and external measures would be available for the environmental monitoring, crew performance, and physiological status, along with methods of crew observation.

The above, of course, describes the ideal integrated simulator which does not exist as such, mainly on the grounds of economy. Comments on the economy of integrated simulators have been made by Smith and DeRocher [64] and by Thompson and Luton.[68] The former note that initial cost tends to be set by the complexity of the desired simulation, size, frequency response, automaticity of data reduction, and the cleverness of the designer. They do not state whether the designer's cleverness increases or reduces the cost. In studies by Thompson and Luton, they set, as 100 percent of cost, a basic six-degrees-of-freedom simulator responsive to operator control and representing in real time all phases of boost, orbit, reentry, glide, approach, and landing. Adding a moving base for proper direction of acceleration forces and translational motions represented 114 percent. A planetarium raised the cost to 116 percent; pressure, heat, noise, vibration, and atmosphere represented 175 percent, and the addition of a centrifuge raised the cost to 650 percent of the basic. These costs are illustrated in figure 6.

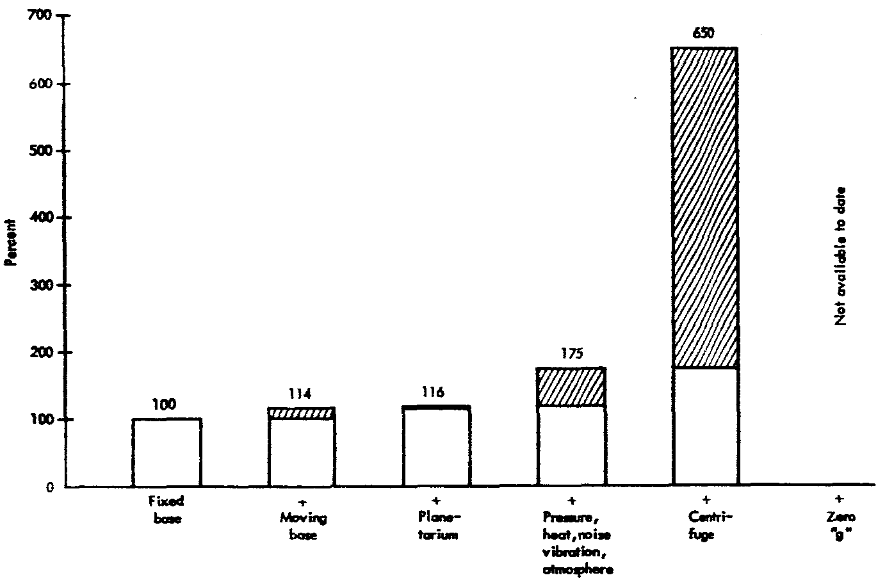


Figure 6.—Relative cost of degree of simulation for space vehicles. (Source: Thompson and Luton [68])

Within the limits of reasonable economies, however, several integrated simulators have been built, incorporating many ideal features. Some of these are detailed in papers by Albright et al.,[3] who describe the uses of high vacuum chamber at Republic Aviation in Farmingdale; Aronson,[4] who discusses the simulator at the U. S. Naval Training Device Center; Barnes,[5] who presents the English Electric Simulator; Brown,[12] who describes the Martin-Baltimore Simulator; Buckhout et al.,[12] who describe the Grumman-New York Simulator; Butler,[14] who outlines the Gemini simulator at Cape Kennedy; Lybrand et al.,[34] who detail the requirements for the Air Research and Development Simulators; Little,[32] who describes the simulator used by General Electric Missile and Space Division; Prodan,[49, 50] who describes the simulator at the Aerospace Research Pilots' School; Xhignessee,[75] who discusses simulators used in France; and Smith and De Rocher,[64] who describe the Martin-Denver simulator. Others are used by Bell Systems, Niagara Falls; Boeing Aircraft, Seattle; Ling-Temco-Vought, Dallas; Hughes Aircraft, Culver City; McDonnel Aircraft, St. Louis; North American Aviation, Columbus and Downey; Space Technology Laboratories, Redondo Beach; IBM Space Guidance Center, Owego, New York; and the Douglas Missile and Space Systems Division, Santa Monica.

Certain aspects of integrated mission simulation require special consideration, and, of these, space rendezvous, docking, and lunar approach and landing are currently of particular importance. Several integrated simulators have the capacity for visual presentation of rendezvous and docking, and some partial task simulators have been designed for the purpose (Neuberger,[42] Prodan,[50] Smith and De Rocher [64]). Smith and De Rocher, in particular, have analyzed some of the problems of rendezvous and docking simulation. They distinguish between closure and docking, the former being from a few hundred feet of separation distance until the first contact and the latter being from the first contact until secure fastening. They maintain that a closure and docking simulation must provide accurate reproduction of rendezvous sensor characteristics, including visual inputs to the pilot control systems, and that orbital vehicle dynamics, as well as the docking device geometry and forces, should be reproduced. They consider it unrealistic to break the action into separate phases and believe that the entire period should be simulated without a break. They also note that rendezvous may be divided into different classes—cooperative, uncooperative, manual, and automatic—each of which has different simulation problems. They discuss some of the desirable features of a docking simulator, noting in particular that its design should be adaptable to a wide range of vehicles and to a variety of docking mechanisms, such as the "probe and drogue," whereby an extendable boom system is mated while the vehicles are still separate; the "net" systems, using extendable and retractable nets; or the "mouse on a string" system, in which a small controllable vehicle, the "mouse," is attached to one of the main vehicles by a cable with control and power wiring. The "mouse," when required, is flown to the other vehicle and attached, after which the two vehicles are drawn together by the cable.

The primary need of rendezvous simulation techniques is the provision of display information on the attitudes, relative positions, and motions of the two vehicles, and external visual information matched to the simulated situation to assist in guidance and control. At the Langley Research Center, two types of rendezvous and docking simulators are being used to determine handling techniques for the Gemini vehicle. In one, a vehicle suspended from a travelling dolly makes actual contact with a dummy Agena target vehicle under visual guidance from the operator; in the other, an out-of-the-window projected TV display is used to provide the target. Different approaches lend themselves to different aspects of the problem.

Simulation of lunar approach and landing is also being undertaken at Langley. One simulator, the lunar orbit landing approach simulator, features a highly sophisticated out-of-the-window projected TV display which provides a representation of the lunar surface. The maps, which are the basis of the visual system, include a lunar globe and representation of the lunar surface on three different scales. The TV camera tracking system simulates the landing approach from an altitude of 200 miles down to 200 feet, at which point the lunar landing simulator takes over. Thus, several different simulators are used to represent what is actually a continuous task. This is largely determined by engineering limitations; however, for continuous tasks, it is probably better to provide continuous simulation whenever possible.

There is probably also a place for the use of integrated mission simulators in the training of in-orbit maintenance tasks.

Part-task simulation

Part-task simulation has a place in both training and research, when the original task or situation can be analyzed into components; in each, training or investigation is needed. A possible requirement has already been noted with respect to obtaining basic long-duration data. In part-task simulation, of course, no attempt is made to include all the aspects of a particular mission or even in a particular environment. Only those aspects which are of immediate interest to the investigator are included. In some respects, any form of controlled scientific investigation involving man's function in his environment is a part-task simulation, but the term in the aerospace field mainly refers to the use of procedures trainers, flight trainers, and devices simulating specific aspects of a problem. Procedures trainers are designed specifically for training in particular tasks and sub-tasks, normal and emergency. They may vary from a simple piece of apparatus to a fairly complex simulation of a cabin in which the requisite procedures are simulated to the degree required. A flight trainer provides for general flight (or space) training without simulating any particular vehicle and without reproducing all aspects of the environment.

As pointed out before, one of the major problems that arises in the use of simulators concerns the validity of the transfer from simulation to actuality. While this is a problem highly pertinent to the design of integrated mission simulators, it is even more of a problem in the design of part-task simulators. In the former case, every attempt is made to reproduce maximum feasible physical and perceptual equivalence, and although experimental validation is still required, face validity, at least, is more readily apparent. Whether actual validity exists requires verification. With part-task simulators, however, even more difficulty is encountered, although it is easier to produce high fidelity in a component of a total mission than for the entire mission. There is little doubt that when one measures man's response in a rotating centrifuge, one is largely measuring man's response to sustained acceleration. But when one provides an astronaut with training in a centrifuge programed to simulate a launch profile, but otherwise considerably different from the launch environment, is this training applicable to the real-life situation? Secondly, in using part-task simulation for research purposes, how much is lost by eliminating environmental interactions?

This raises the general question of part versus whole learning, which has been examined with respect to simulation by Muckler et al.[40] They point out that, while much general work has been published on the relative efficiency of part versus whole learning and many factors are involved in creating a greater effectiveness of one method over the other, most of the studies have been concerned with verbal or simple psychomotor learning and very few with the more complex tasks. The general consensus, however, would appear to be that, while whole task learning is probably superior, part-task learning can be substituted if required, with little loss in training efficiency or final level of skill achieved. Miller [37] has made an analysis of the problems of part-task and whole-task training with respect to flying training, and describes techniques for analyzing a flying task into component parts suitable for examination and training in part-task or job-segment simulators. He points out that any standard routine procedure that is not time-shared with other activities can be taught as an independent training segment and that many of the routines underlying nonstandard procedures are susceptible to part-task training. Sometimes, however, even time-shared tasks, if unusually difficult, are best practiced separately at first and then combined. In general, he considers that training activities can be classified as familiarization training, instructed response training, and automatized skill training. For each of these areas, different forms of simulators are required, as illustrated in table 3. This type of analysis would appear to be a logical approach

Table 3.—MINIMUM PRINCIPAL DISPLAY-CONTROL REQUIREMENTS OF TRAINER TYPES (SOURCE: MILLER [37])

Types of trainers	Essential form of display	Essential form of control	Result of training
	Familiarization trainers		
Demonstrators	Symbolic-diagrammatic in two or three dimensions	None required; response is symbolic	Motivation background for learning and performance; knowledge background; may include some "nomenclature" and "locations" training
Nomenclature and locations trainers	Diagrammatic; non-functional mock-up; miniatures	None required; response is symbolic	Basis for memorizing and executing job instructions

Table 3.—MINIMUM PRINCIPAL DISPLAY-CONTROL REQUIREMENTS OF TRAINER TYPES (SOURCE: MILLER [37])—CONTINUED

Types of trainers	Essential form of display	Essential form of control	Result of training
	Instructed-response trainers		
Detection of condition trainers	Simulation of displays in critical work environment; displays may be intermittent or continuous. Models	None required; response is symbolic	Scanning techniques; perception through noise; detection of absolute values or relative changes in displays
Identification of condition trainers	(1) Symbolic or diagrammatic (2) Simulation of critical displays plus work-context cues in later training	None usually required; exception when controls must be used to get data; critical response is symbolic	Response to *patterns* of display data; inference making about conditions; rapid perceptual response; short-term recall
Problem-solving and decision-making trainers	(1) Symbolic or diagrammatic (2) Simulation of critical displays may be miniaturized (3) Response correction should schematize correct decision process	(1) None required; response is symbolic (2) Nonfunctional or diagrammatic as part of display problem May be miniaturized and/or schematized	Variables in required decision; inference making; short-term recall; response alternatives and implications
Instructed-response trainers for procedures	(1) Diagrammatic (2) Discrete-valued displays; discrete-valued response to control activation. (Symbolize or represent conditions under which procedure itself should be initiated). May be miniaturized	Simulated for relative location, direction of movement; control forces irrelevant; may be miniaturized	Long-term conceptualization of steps in a procedure; precautions; threefold association of environmental stimulus, conceptual stimulus, conceptual response, and overt response

Table 3.—MINIMUM PRINCIPAL DISPLAY-CONTROL REQUIREMENTS OF TRAINER TYPES (SOURCE: MILLER [37])—CONCLUDED

Types of trainers	Essential form of display	Essential form of control	Result of training
	Automatized skill trainers		
Tracking trainers	Simulated tracking displays; simulated control-display interactions. Other displays to be scanned may be discrete-valued	Tracking controls; in compensatory tracking, control forces and amplitudes well simulated; in pursuit tasks, less simulation required	Anticipations of target motions and of "cursor" capabilities (i. e., display-control dynamic interactions)
Job segment trainers, simulators	Full simulation (with some qualifications)	Full simulation (with some qualifications)	Integration of part tasks; time-shared or time-linked activities; automatized habits; proficiency evaluated and diagnosed

to determining the required partition of part and whole-task simulation and has application to manned space simulation. The same principle is probably applicable to the use of part-task simulation for research purposes. Much experimental work, however, remains to be done to validate the conclusions.

Jones (personal communication) points out that a significant factor influencing selection is that where more than one set of crewmen are trained for a mission, each crewman of a set will have different training schedules, except for moderate amounts of integrative training. Thus, the bulk of training is individually oriented, and full real-time mission training will generally be wasteful. This is particularly so in spacecraft, as opposed to aircraft, since, in the former, long periods can elapse without the occurrence of significant events. Segments of short duration and high activity must be practiced to make full use of training time. Jones, in fact, claims that a fully unified simulator is usually not desirable except if dictated by flight crew acceptance needs. While this is a strong view, it is clear that selection of a part-task versus whole-task simulator should be influenced by cost and schedule tradeoffs. He also presents in tabular form (table 4) other factors influencing such a selection.

It is also interesting to note the comments of Prodan [49] of the Aerospace Research Pilot School, who states: "The philosophy of part-task simulation, which earlier was adopted out of necessity, has considerable merit. This type of simulation is ideal for the normal progression of the pilot through his academic training. He studies boost trajectories in class and then flies them on the simulator without being concerned with such things as reentry problems. These he will fly after appropriate class work. For this reason, the School plans to continue part-task simulations. . . ." These views are borne out by the wide acceptance of flight and procedures trainers by air forces and civil airlines.

Thus, while partial simulation has particular value in providing a means for determining man's response to his environment and for evaluation of human factors concepts, it also has a place, although perhaps on a somewhat empirical basis, in training.

Environmental simulation

Environmental simulation is, of course, a form of partial simulation, although it can vary in sophistication and complexity from a simple pressure or temperature chamber to an extremely complex environmental space chamber (Schueller;[61] Schueller and Berner [62]). A comprehensive list of environmental simulation facilities is included as an appendix to an AGARD report

Table 4.

FACTORS INFLUENCING CONFIGURATION OF SIMULATORS
(SOURCE: JONES, PERSONAL COMMUNICATION)

	Favors part-task simulator concept	Favors unified mission simulator concept
Spacecraft design: Crew compartment layout Control-display layout Experiment packaging	Design where the crew module tends to be stable from flight-to-flight and experiments portion variable, where control-display layout separates vehicle and experiments functions, and where crew compartment layout is designed for zero-g operation and must be configured for one-g operations	Design where both crew and experiment portions tend to be stable from flight-to-flight, where control-display layout integrates vehicle and experiment functions, and where crew compartment layout allows use in one-g environment
Crew task characteristics: Time-sharing of tasks Time-sharing of segments	Crew task allocation where tasks involving different systems tend to be separate, and where spacecraft segments are independent	Crew task allocations where difference systems are operated together, and where spacecraft segments are time-shared (experiment and laboratory vehicle system operation)
Training Techniques: Diagnostic training Real or part-time Mission rehearsal	Training program where emphasis is based upon individual's progress, and where parts of mission are repeated without reference to the mission time-base	Training programs where each crewman is given the same practice, and where missions tend to be rehearsed on a real-time basis
Measurement techniques: Problem repeatability and control Recording devices	Measurement techniques where objective data are required on relatively discrete and standard tasks that must be repeated frequently enough to obtain statistical reliability	Measurement techniques oriented more around subjective measures and where large segments of the task are repeated allowing variability from trial-to-trial based upon decisions made by the crew
Fidelity requirements: Areas of extremely high fidelity	Design where fidelity requirements for specific parameters are very high, such as simulation of atmospheric effects or star fields, and cannot be met readily when combined with other design features	Design where a long sequence of tasks is involved, or where crew decisions can lead to several other courses of action, particularly as related to programming or reprogramming a series of experiments, demand that many parameters be simulated

Table 4—FACTORS INFLUENCING CONFIGURATION OF SIMULATORS (SOURCE: JONES, PERSONAL COMMUNICATION)—CONCLUDED

	Favors part-task simulator concept	Favors unified mission simulator concept
Division of crew functions: Exclusive Independent Time-shared	Utilization concept where a function will be required only of one crewman, or where the same function is accomplished independently by each crewman	Utilization concepts where the crewman cooperate in performing the same task and where system becomes more operational demanding such productive crew interactions
Flight crew acceptance: Motivation Wait-times	Design where the essential tasks are high fidelity and non-essential low fidelity is apt to have increasing motivational value after crews understand compromises, or where long periods of waiting are required because mission time-base cannot be altered or tasks repeated	Design where the appearance of the simulator is closest to that of the flight vehicle is apt to have greatest "face" validity for the crew, particularly when they are first introduced to the devices
Flight vehicle training potential: Pre-flight On-orbit	Training concepts where flight hardware can be used for final mission rehearsal, or where operational concepts allow final training on-orbit for task elements difficult to simulate such as extravehicular activities	Training concepts where flight hardware is not available for final mission rehearsal, or operational concepts where tasks (safety of flight) cannot be rehearsed on-orbit
Availability: Part-task use Reliability Capability for accepting minor modifications	Utilization concepts where part-task use of device is necessary, where system reliability is high, and where modifications can be accomplished without affecting too great a percentage of the training tasks	Unified simulator design concept is possible where building-block approach allows quick repair or modification of simulator systems in a manner that does not interfere with training for other tasks
Schedule: Availability for first mission Availability after modification for subsequent missions	Design approach where as reliable device as possible is available prior to first manned missions, and where modifications to "leap-frog" to next mission can be accomplished with minimum sets of equipment	Program schedule where development cycle is long, where experiment changes from mission-to-mission do not require significant modification of simulators, and where simulator design can wait upon testing of actual prototype or operational equipment

by Westbrook,[72] which illustrates the variety of environmental factors that can be simulated.

One factor, however, null gravity (or weightlessness), is still beyond simulation except for very short periods. Loftus and Hammer [33] discuss some of the approaches that have been made to this problem. One of the methods that has received considerable attention is that of causing an aircraft to fly a so-called Keplerian trajectory, which, in effect, is a dive followed by a segment of an outside loop. The radius of the loop is so chosen that the centrifugal force developed balances the gravitational force acting on the aircraft and its occupants and effectively produces a nulled gravitational state. Periods up to 90 seconds of weightlessness have been produced by this method. This duration, however, is far from adequate to permit study of the full body response to the weightless state, and in addition the preweightless acceleration, the coriolis effects, vibration, noise, perhaps reduced pressure, and other variables contaminate the simulation.

Another approach has been to reproduce one of the outstanding characteristics of zero g, namely, the inertial movement of bodies. This can be achieved in the horizontal plane, even in the presence of gravity, by the use of airbearing devices in which an air cushion is created between two polished surfaces. The resulting platform provides a very low friction contact. Some of the work in this field is described by Dzendolet.[21] Loftus and Hammer [33] draw attention to the need for caution in interpreting data obtained in these procedures, since the inertial effects of force exerted in a particular action will be reflected into the plane of free motion and are not necessarily the reactions that would take place if all axes of movement were completely free; also, the gravity vector remains in the system. This is particularly noteworthy in that gravitational action on the vestibular system and proprioceptive sensory nerves is not eliminated.

Another approach has been to simulate some of the physiological and sensory responses to weightlessness by water immersion (Knight[30]). Again, however, these methods and, for that matter, the use of bed-rest, while representing a perceptual equivalence of certain aspects of weightlessness, do not in fact simulate weightlessness. Other methods, such as elevators and drop towers which use the "free fall" concept, have also been suggested but provide extremely short-term durations.

Recently, considerable attention has been devoted to simulating reduced gravity states such as those found on the moon. The systems employed generally utilize some form of harnessing and low friction pulleys so devised that they counterbalance the necessary amount of body weight and allow up to a six-degree of freedom of movement. The simulation, however, is imperfect, since not only does the harnessing and suspension create problems not present in the real-life situation, but the gravitational vector remains continuously present and exerts its normal action on the vestibular and proprioceptive systems. It is, however, a useful method for determining locomotor ability. The techniques, findings, and problems in this type of simulation have been thoroughly analyzed by Roth.[56]

Thus, while approaches are being made to the simulation of weightlessness and reduced gravity states, even perceptually equivalent simulation remains as yet unattainable.

CHAPTER 5

DISCUSSION

The preceding discourse has indicated that the art and science of simulation evolved out of necessity as a tool for the investigation of situations, tasks, and problems which, for various practical reasons, could not be examined in their actuality. While having application, in one way or another, to almost all the sciences—physical, human, and social—it has found particular application in the investigation of engineering and psychophysiological problems of space flight. Starting as a technique for the simple representation of the essential elements of a problem, it took a giant step forward with the development of electronic optical and computer sciences, particularly with the mating of the analog and digital computer. These same developments, however, have introduced a new problem in that with the use of sophisticated technology it is possible to simulate, with remarkably apparent realism, environmental and other situations, the parameters of which may be incomplete, open to unknown bias, or merely speculative. Basing measurements and observations on such simulation is hazardous.

It is necessary then to reemphasize certain principles which can be inferred from the previous discussions, but which perhaps tend to be overlooked by those who naively consider that simulation will provide a solution to most of their problems. These principles may be stated as follows:

(1) A situation, task, or problem can be simulated in a valid manner only insofar as its parameters are known.

(2) A simulation can provide the solution to a problem or provide valid information, only if the elements of the solution or the information reside in that simulation.

(3) Simulation may provide an incorrect solution or false information if the simulation is incomplete or the parameters of the simulation are incorrect.

(4) Only those parameters of a situation, task, or problem necessary for completeness of the simulation need be represented in the simulation.

Within those bounds, simulation has a valuable place in the investigation of, and preparation for, manned space flight, although there must always be the cautious observation that because of recognized lack of knowledge, or what is worse, unrecognized lack of knowledge, the simulation may be incomplete. It may be equally difficult to determine what parameters to simulate. The resulting choice may be arbitrary, in which case the final simulation and, accordingly, dependent measurements, may be biased.

As has been noted, the systematic approach to simulation along the lines of the classical experimental method is likely to produce the most reliable results. All authors are in agreement on the importance of task analysis or definition of the problem as a mandatory initial step. For the more complex simulations, however, a detailed analysis is often very difficult, if not impossible, since often some of the significant parameters which should be carefully analyzed are those same factors for which knowledge is being sought. Hence, there is a danger of developing a circular form of reasoning. On the other hand, haphazard approaches must be deplored. As Westbrook [72] says: "Most serious of all is the type of attitude that sometimes develops, to simulate without thinking. This is deadly. It results in blind repetitive programs of little real worth. It is the opinion of the author that in Europe this condition is less prevalent than in the United States. Lack of a simulator may encourage the development of a more basic understanding of a phenomenon. This is not to imply opposition to simulation. On the contrary, rather is it a plea for its intelligent use."

There is no doubt, however, that in many places intelligent use of simulators is being made. At the same time, there is perhaps a tendency for simulator workers to demand more and more sophisticated and costly simulators to determine factors which might well be obtainable on simpler devices, and for simulator designers to become so enthralled with the fascination of their work that to them simulation is an end in itself instead of an information tool.

General requirements for simulation as a tool in manned space flight activities were examined in the main text. From the discussion it may be concluded that the value of simulation depends upon the fidelity with which simulation represents actuality. For some cases, notably in operational research or in the evaluation of function, physical fidelity is the keynote, whereas for training and proficiency testing, perceptual fidelity is required. The key to perceptual fidelity lies in the creation of illusions and a false perception of orientation.

While it is a guiding principle that only the essential parameters need be simulated, in some of the more complex simulators, a degree of physical fidelity is necessary, particularly, for example, in replication of a cabin appearance. It is doubtful if other aspects of the internal cabin environment, such as pressure, temperature, and humidity, need be simulated, except in investigations involving these parameters, although noise provides a feeling of realism.

One of the major problems lies in the provision of motion and its related phenomena. It would seem that moving simulators designed for the investigation of the effects of motion, such as centrifuges, vertical accelerators, shake tables, rotating rooms, etc., and in the same category might be included variable stability aircraft, are invaluable in the determination of the response of man and materials to the effects of motion. However, application of motion to a complex integrated simulator is at best a compromise and can provide only a perceptual equivalent. At the same time, it would seem that this perceptual equivalent is of value in training and familiarization and should be provided within the limits of reasonable economy. In some situations, such as rendezvous and docking or landing, it is essential to provide a perceptually equivalent motion, although this may be provided as a visual illusion.

It would also seem that certain external visual displays are mandatory in the complex integrated simulator, such as in the rendezvous, docking, and landing situations mentioned above, and for experience in terrestrial observation and celestial navigation. In other situations, they serve the purpose of promoting realism only and do not seem essential.

The uses and potential applications of simulation in the manned space field are broad, but are found in three main areas; operational or engineering research, psychophysiological research, and training. A fourth field, selection, is suggested, although much work will have to be done, particularly in the field of physiological and psychological performance and proficiency testing, before simulation can be deemed reliable. Comments and suggestions on various other problem areas have been made in the text, but some require emphasis.

One problem in the psychophysiological research field is related to the difficulty of extrapolating results from the simulator to actuality. In the case of the partial simulator, such as the centrifuge, while it provides reliable data on the human response to an isolated stress, it is difficult to assess the significance of the findings in relation to the total picture, since isolated stresses do not occur in actuality. Consequently, more information is needed on the response to carefully controlled double and multiple stresses and the relationship of those responses to the total response. This problem is related to the part versus whole simulation controversy which has been noted and will be discussed.

On the other hand, extrapolation of the findings obtained on a complex integrated simulator to the requirements of actuality is also hazardous for reasons that have been noted; much work is needed on development of techniques that will reliably predict the expected human response to a widely changing environment on the basis of past measurements of physiological and psychological function in another widely changing environment.

A related and even more pressing problem is the determination of the duration of simulation required to qualify a mission or, alternatively, the duration of simulation needed to predict when failure will occur. This is a problem which has beset engineers as well as life scientists, who as yet have found no satisfactory answer. The problem, however, requires a systematic examination to determine the shape of the curve suggested in figure 6 and the point at which simulation duration should match mission duration. This point of course will inevitably be established on the basis of economics as well as psychophysiological knowledge. Data for this purpose, however, will take a long time to be acquired.

Meanwhile, to qualify long duration missions, it would seem necessary either to simulate them in their entirety, which is impracticable for durations of over a few months, or to tackle the problem from another aspect, determining independently the maximum capacities of man including his response to long duration single or multiple stress, assessing his reliability within the framework of a total long duration mission, and tailoring the mission accordingly.

In the training field, while there are still fundamental areas of learning theory that are the subject of controversy and numerous problems of detail that require settling, such as control/display relationships, etc., one of the major problems needing attention is that of determining the value and best use of part-task in conjunction with whole-task simulation. There is no doubt that each can be used with profit; but while several studies exist on the value of part-task learning, there is little work on the comparative use of part-task and whole-task simulators. Much more information is needed on the relative transfer of training that accrues from part-task simulation, as opposed to that from whole-task simulation with respect to a real-life task, and also the transfer that accrues from part-task training with respect to an integrated simulator task. While both part- and whole-task simulators are being used at this time for training purposes, the division of training is somewhat arbitrary. With increasing knowledge, a systematized approach will become more practicable, whereby some aspects of training can be relegated to simple part-task trainers or single stressors, some to more complicated trainers or multi-stressors, while the whole is finally coordinated by the use of complex integrated mission simulators. In each case, however, knowledge is first required on the expected adequacy of the transfer of training.

A comment remains to be made on the simulation of one aspect of environmental stress—weightlessness or a reduced gravitational state. Intuitively, until we achieve the science fiction dream of anti-gravity, this simulation would seem impossible; however, it is evident that much can be gained by continuing attempts with counterbalanced harnessing, water immersion, bedrest, and the like, to represent aspects of this phenomenon. At the same time, it is emphasized that, with these techniques, some major effects of weightlessness are ignored, particularly, those on the vestibular organ and the proprioceptive portion of the nervous system. Even devices which attempt to nullify or counteract the functions of the vestibular system are in fact providing only a perceptual equivalence of weightlessness. Thus, while these techniques may be used for certain aspects of locomotor, cardiovascular and biochemical investigation of reduced gravity states, they are not actually simulating weightlessness.

CONCLUSIONS

The conclusions that arise from this examination may be stated as follows:

(1) In the design of manned space vehicles and the preparation for manned space flight, simulation, when properly used, can make notable contributions in four main areas: operational and engineering research, psychophysiological research, familiarization and training, and selection of astronauts.

(2) Proper usage of simulation is predicated upon adequate knowledge of the parameters to be simulated; development of a careful experimental, training, or selection, protocol; and selection of a suitable simulation system which will represent the required parameters with necessary fidelity.

(3) Obtaining an adequate knowledge of the parameters entails careful analysis of the task or tasks to be simulated; the environment in which they are to be simulated; and an examination of the potential interactions occurring in man, task, and environment. Much information required for this purpose, particularly for future space mission, is ill-defined and subject to guesswork. Simulation based on guessed or extrapolated parameters may well be invalid.

(4) When the parameters are known, the value of simulation depends on the fidelity with which these parameters are represented. Fidelity may be both physical and psychological. Difficulties in achieving psychological fidelity may be reduced by using the concept of perceptual fidelity, or phenomenal equivalence, in which illusions of realism are created.

(5) For the conduct of operational and psychophysiological research, physical fidelity and actual reproduction of the critical

parameters are necessary. For training and selection, perceptual fidelity can often be used to provide an acceptable transfer of training.

(6) It is unnecessary to reproduce all the parameters of a given situation; only those parameters necessary for completeness of the simulation need be represented in the simulation. These parameters, however, are frequently not fully known.

(7) Selection and representation of critical parameters may include a known or unknown bias which can invalidate the resulting simulation.

(8) For a manned space simulator, requirements for physical fidelity in cabin layout, for working realism in displays and consoles, and for control feel and display relationships have not been thoroughly investigated. Work on similar requirements for aircraft simulators suggests that realism in these parameters may not be vital for adequate transfer of training. Much work is required to determine the necessity for realism in this area.

(9) Motion simulation, in part-mission or whole-mission simulators, seems necessary only where the effects of motion are under investigation or where motion affects performance. The latter situations are not fully defined. There is no definite evidence as to whether, in training, motion cues should be incorporated into a full mission simulator or whether adequate transfer of training can be provided separately on a simple simulator designed for the purpose. Perceptual equivalence of motion is of value in visual displays for rendezvous and docking, and perhaps landing, simulators. Because of proprioceptive and vestibular feedback in terrestrial gravity, simulated motion may contribute to negative transfer of training.

(10) The requirement for representation of external vision in a space-cabin simulator depends on the nature of the task or tasks to be accomplished. There appears to be no need to recreate the

entire visual world in any given area, nor is there a requirement to provide a visual simulation for all aspects of a space mission. Facilities are required for presentation of displays governing terrestrial, celestial, and lunar or planetary observation at specific times during the mission, for rendezvous and docking, and for terrestrial or other landing. These facilities will be used for detection, recognition, navigation, and monitoring of vehicle control and extravehicular activity. Color presentations appear useful but not essential.

(11) The duration of simulation required to validate a mission is not known. With prolonged missions (beyond 3 to 6 months) it will no longer be feasible to simulate a mission in its entirety. Much work is required to determine if there is a consistent ratio relating the duration of a mission to a lesser duration of useful simulation of that mission. If there is no such ratio, arbitrary decisions on the suitability of the mission will have to be made on the basis of other evaluations of man's capacity to tolerate single or multiple stresses.

(12) The question of transfer of training accruing from part-task versus whole-task training has not been resolved. It would appear that where a whole task can be discriminately analyzed into specific component parts, at least some of these can be successfully taught with a part-task simulator. Unification of the components might thereafter be developed on a mission simulator, provided that its applicability has, in turn, been experimentally validated.

(13) In all cases, verification of a simulator system's suitability is necessary to determine its validity. Verification requires an experimental comparison of the simulator system with actuality. Where this is not possible, the results obtained from simulation apply only to the conditions of the simulator and can be applied to actuality only with utmost caution.

In brief, the form and extent of simulation to be used in a given situation depends on the purpose for which the simulation is required, and can only be determined after careful examination of the nature of the training or engineering problem under consideration, the significance of the environmental variables, and the expected response of man.

If simulation is required, it will entail some use or combination of environmental simulation and partial-task simulation, or of integrated mission simulation, but only to the extent that such simulation is needed. The use of unnecessarily sophisticated simulation appears to be neither economical nor advantageous, and, under certain circumstances, can fail to produce the transfer desired. Highly sophisticated mission simulation has a place, particularly in the later aspects of coordinated training and familiarization and to some extent in habitability and ecological studies. But since much of the fidelity in the design is of the perceptual type, this kind of simulator does not lend itself to engineering studies or to psychophysiological investigations where physical fidelity is necessary.

The use of simulation in manned space flight presents otherwise unattainable opportunities to the investigator and trainer, and challenges the imagination of the design engineer, but it is a tool, and only a tool, which must be used with care, since haphazard and careless use can both mislead the investigator and misinform a subject.

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